

Measuring Neutrino Oscillations with the T2K Experiment

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for the
The T2K Collaboration



Fermilab Joint Experimental-Theoretical Seminar
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Super-
Kamiokande

J-PARC

The T2K Collaboration
~500 members, 59 institutes, 11 countries

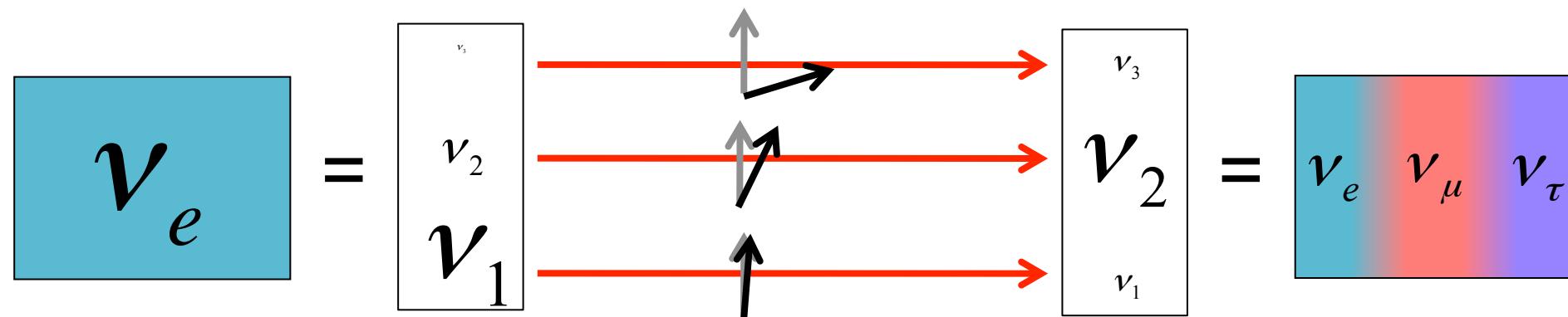


Outline

- Neutrino oscillations
- The T2K Experiment
- Long-baseline oscillation analyses
 - ν_μ disappearance
 - Study of bias from multinucleon interactions
 - ν_e appearance
 - joint fit
 - Potential future sensititity
- Short-baseline oscillation analysis
 - ν_e disappearance to a sterile neutrino

Neutrino Oscillations

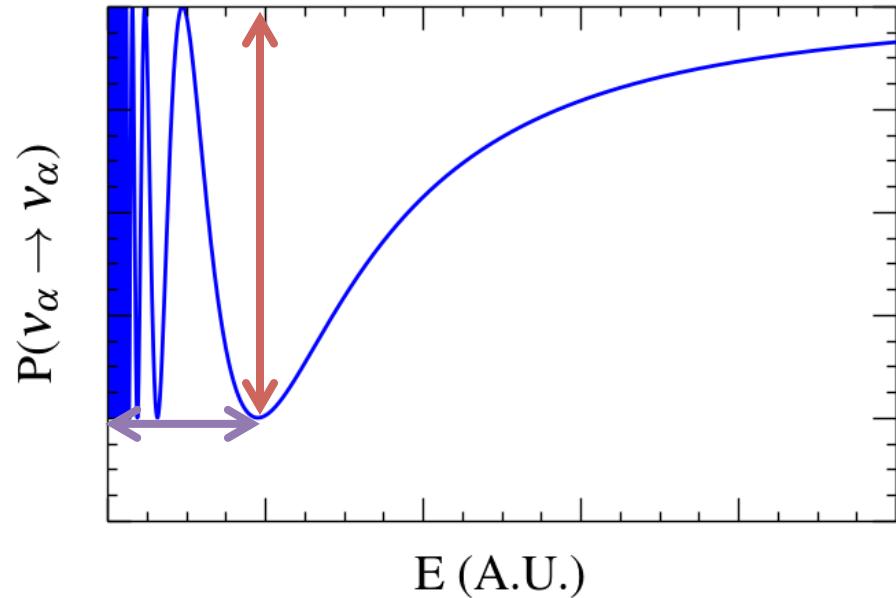
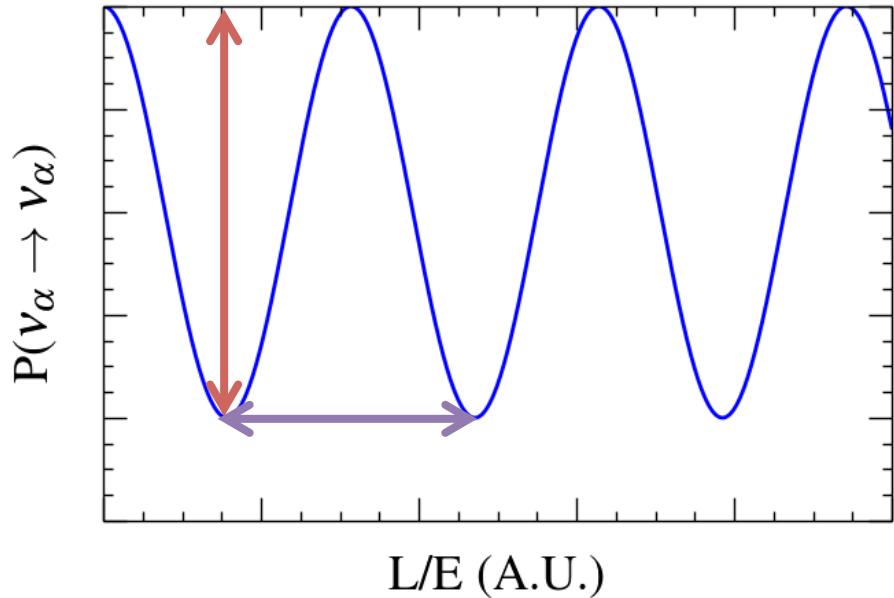
- Interact in weak eigenstates (e, μ, τ)
 - Created and detected in association with the charged lepton
- Propagate in mass eigenstates (1, 2, 3)
 - Phase difference accumulate as they travel, changing the mass and flavor mixture



Neutrino Oscillations

- With only 2 neutrinos, the oscillation formula is simple:

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \boxed{\sin^2(2\theta)} \sin^2 \left(\boxed{\Delta m^2} \frac{L}{4E} \right)$$

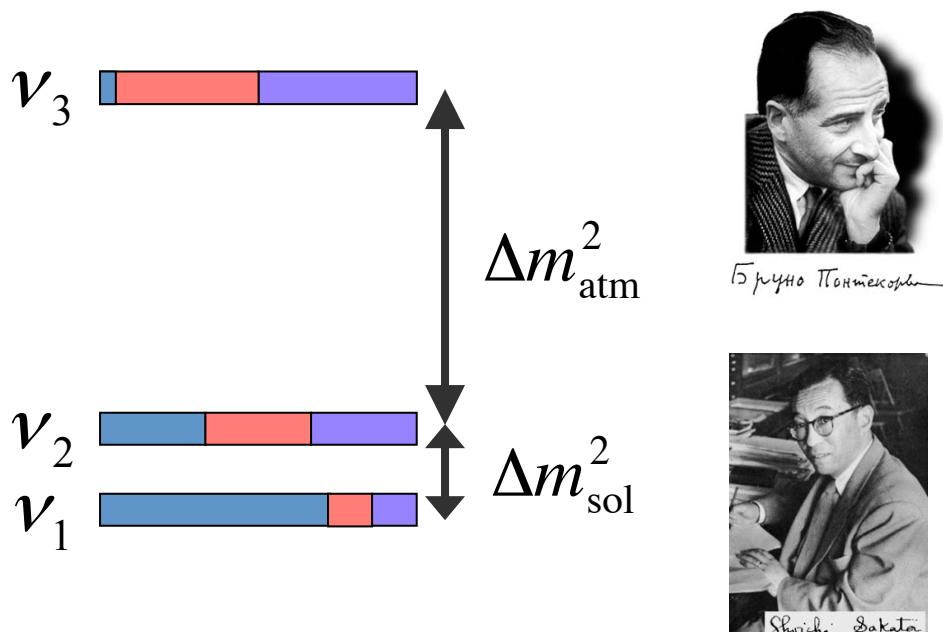


The PMNS Mixing Matrix

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass



Pontecorvo

Sov.Phys.JETP 6:429, 1957

Sov.Phys.JETP 26:984-988, 1968



Maki, Nakagawa, Sakata

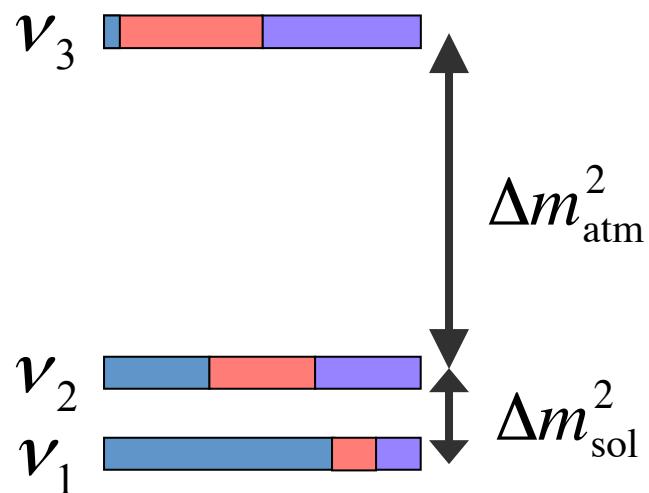
Prog.Theor.Phys. 28, 870 (1962)

The PMNS Mixing Matrix

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass



3 Angles:

1 Phase:

$\theta_{12}, \theta_{13}, \theta_{23}$

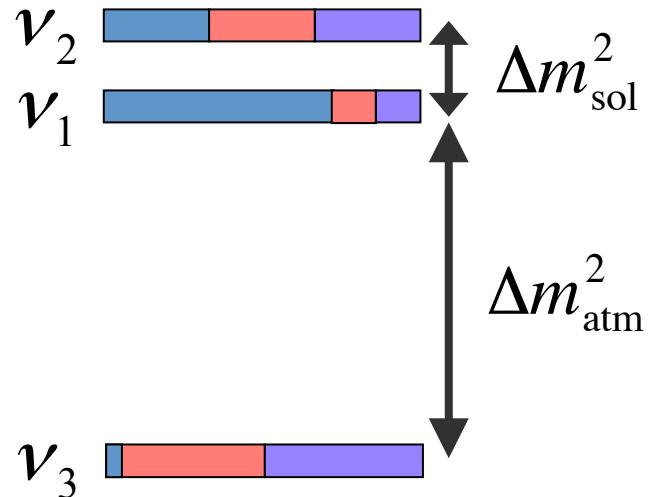
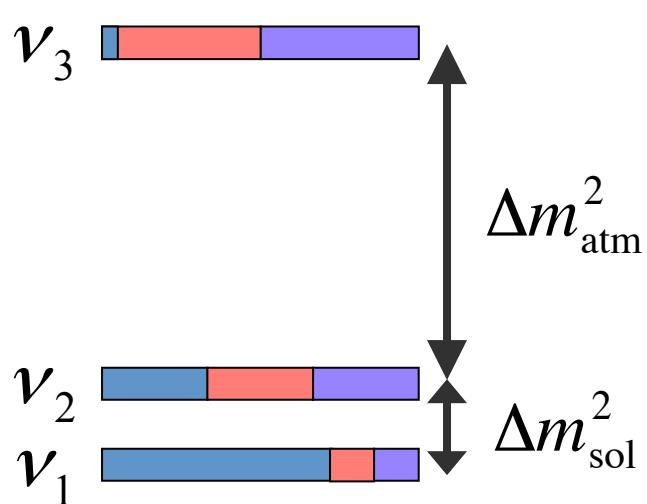
δ_{CP}

2 Mass splittings: $\Delta m^2_{32}, \Delta m^2_{21}$

The PMNS Mixing Matrix

$$\begin{array}{c}
 \text{Flavor} \\
 \left(\begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right) = \left(\begin{array}{ccc} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{array} \right) \left(\begin{array}{ccc} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{array} \right) \left(\begin{array}{ccc} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{array} \right) \left(\begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \right)
 \end{array} \quad \text{Mass}$$

“solar” “reactor” “atmospheric”



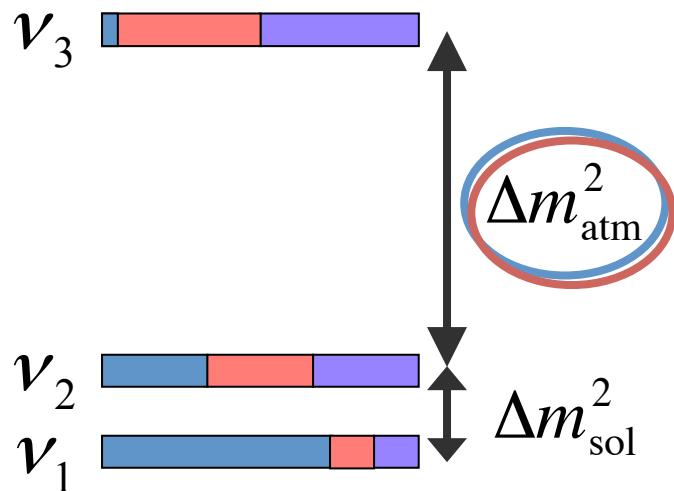
The “mass hierarchy,” or sign of the atmospheric Δm^2 , is also unknown.

Oscillation Physics at T2K

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass



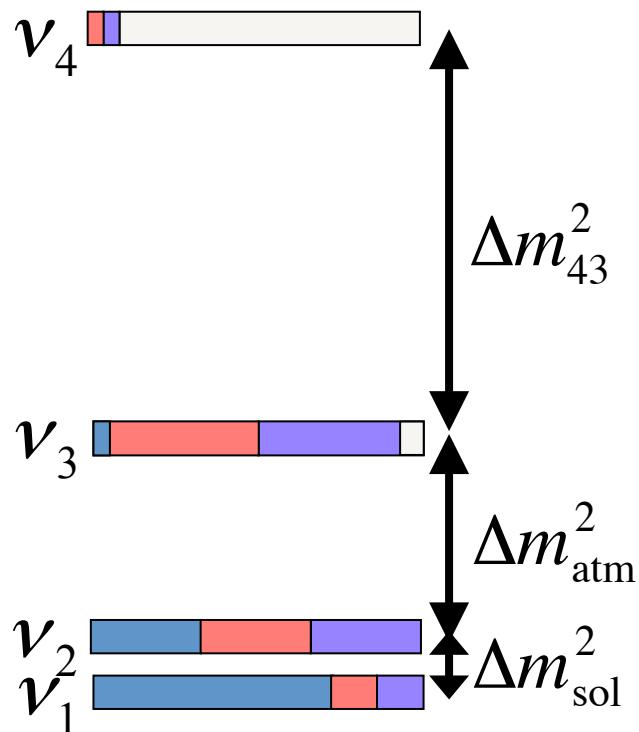
Long Baseline

ν_μ Disappearance: $\theta_{23}, |\Delta m^2_{\text{atm}}|$

$\nu_\mu \rightarrow \nu_e$ Appearance: $\theta_{13}, \delta_{\text{CP}}$

Oscillation Physics at T2K

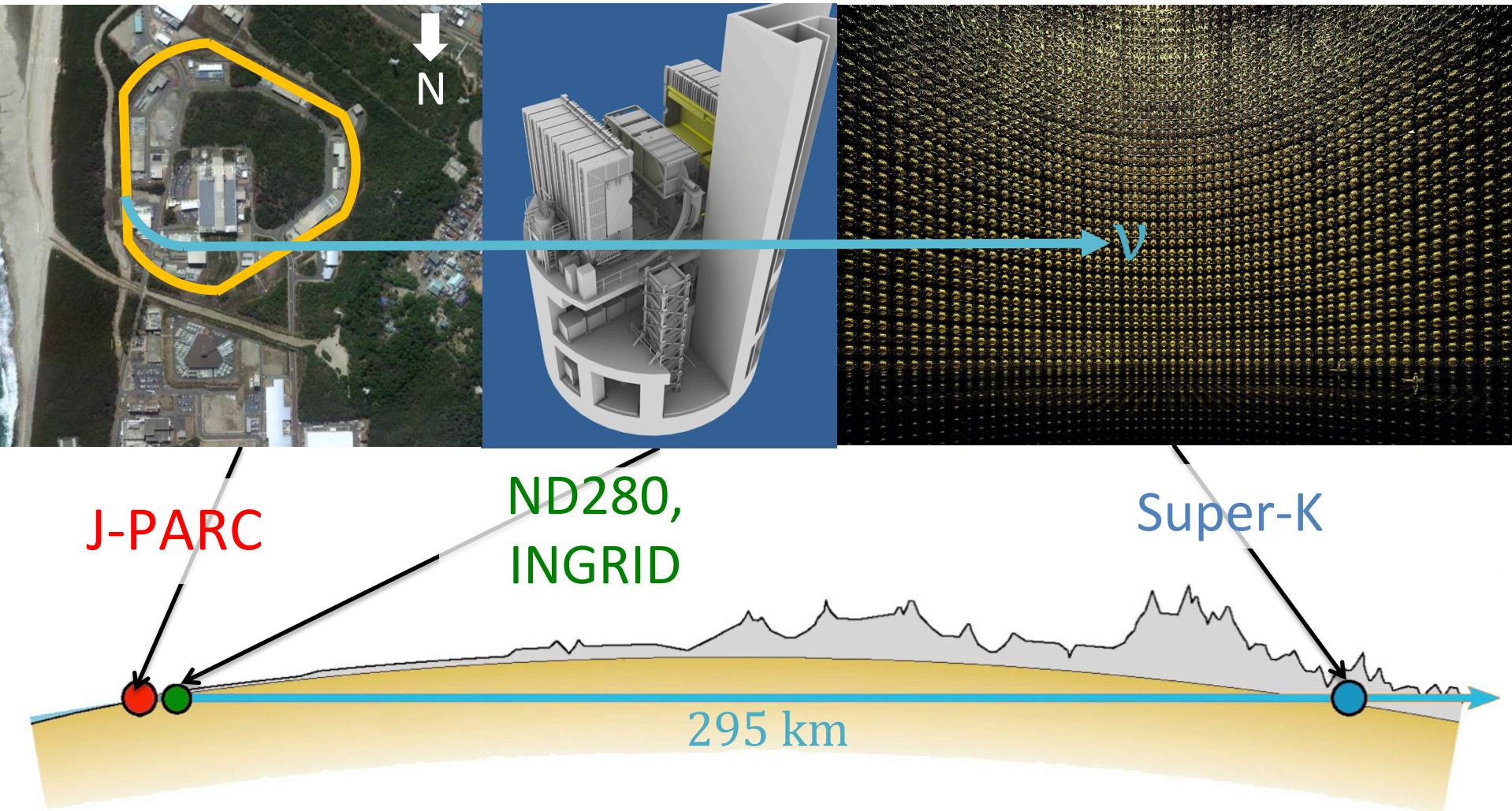
$$\text{Flavor} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U_{\text{PMNS}} U_{\text{sterile}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} \text{Mass}$$



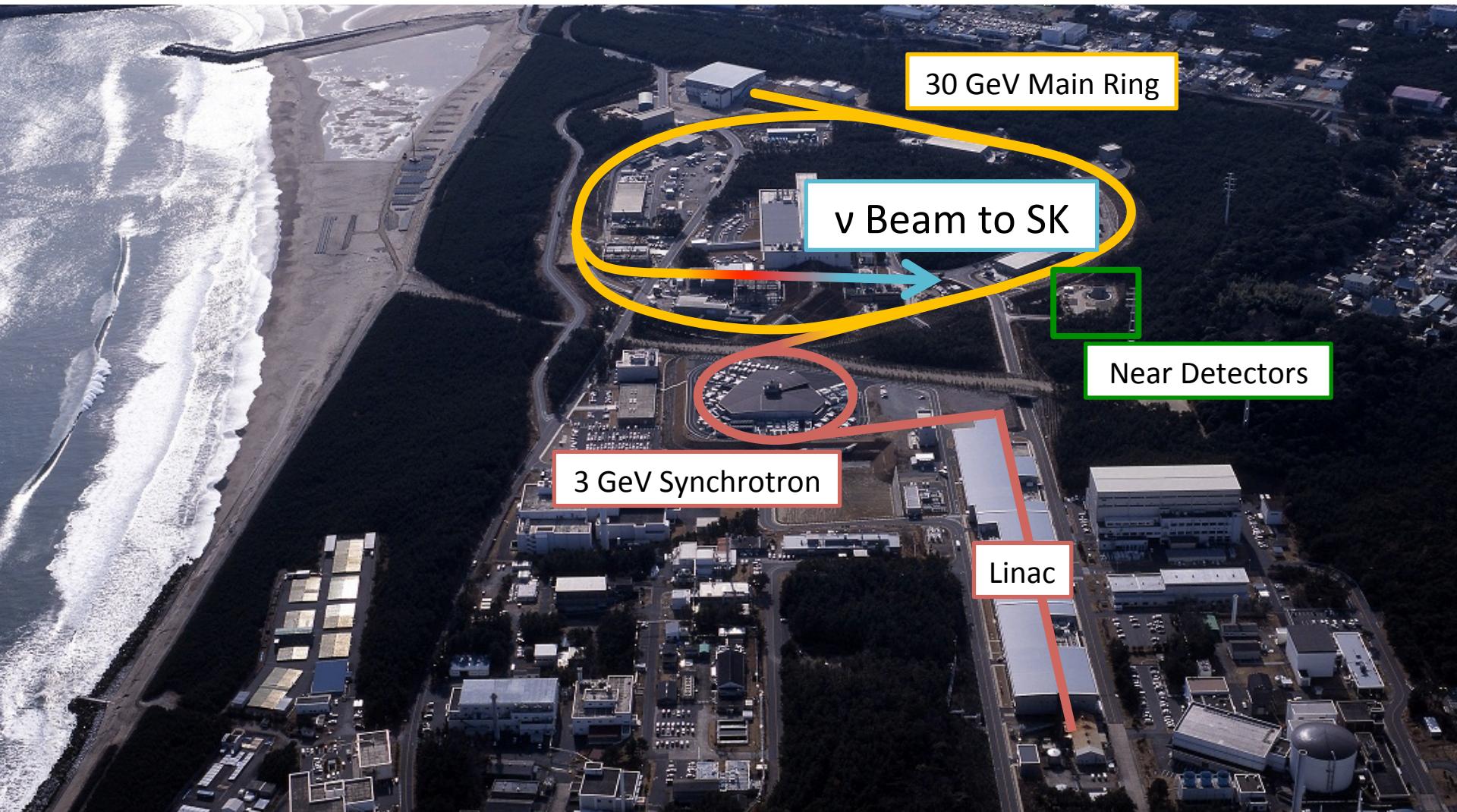
Short Baseline

ν_e Disappearance to a sterile neutrino: $\Delta m_{43}^2, \sin^2(2\theta_{ee})$

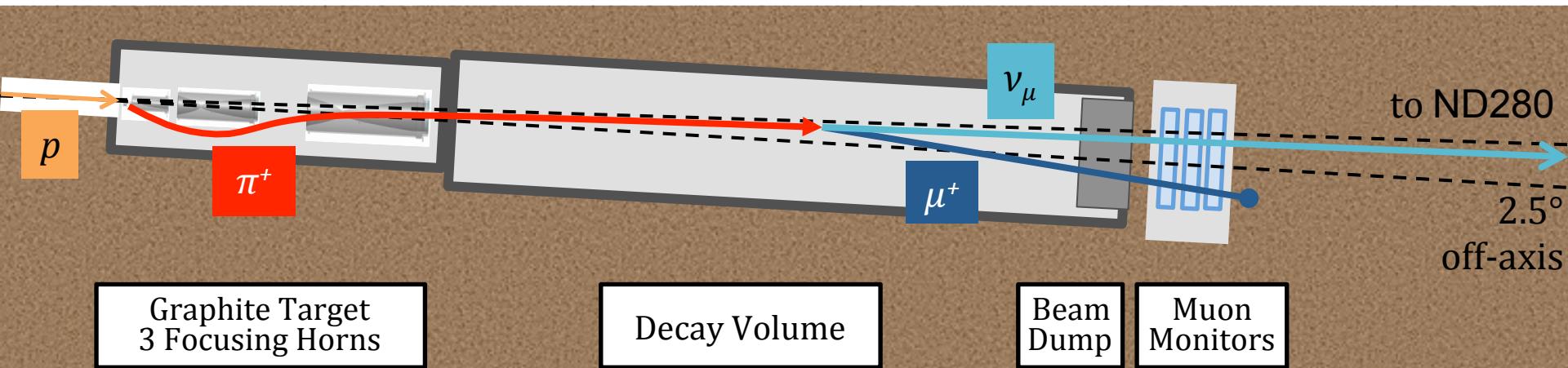
The T2K Experiment



J-PARC

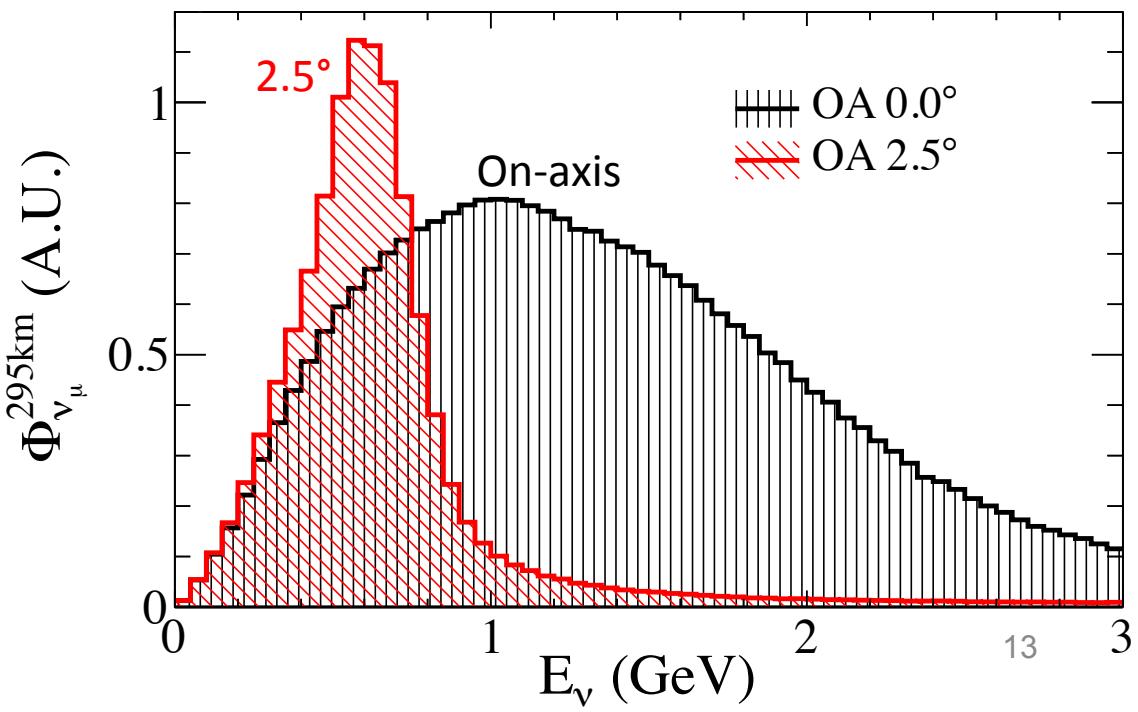


J-PARC Neutrino Beam

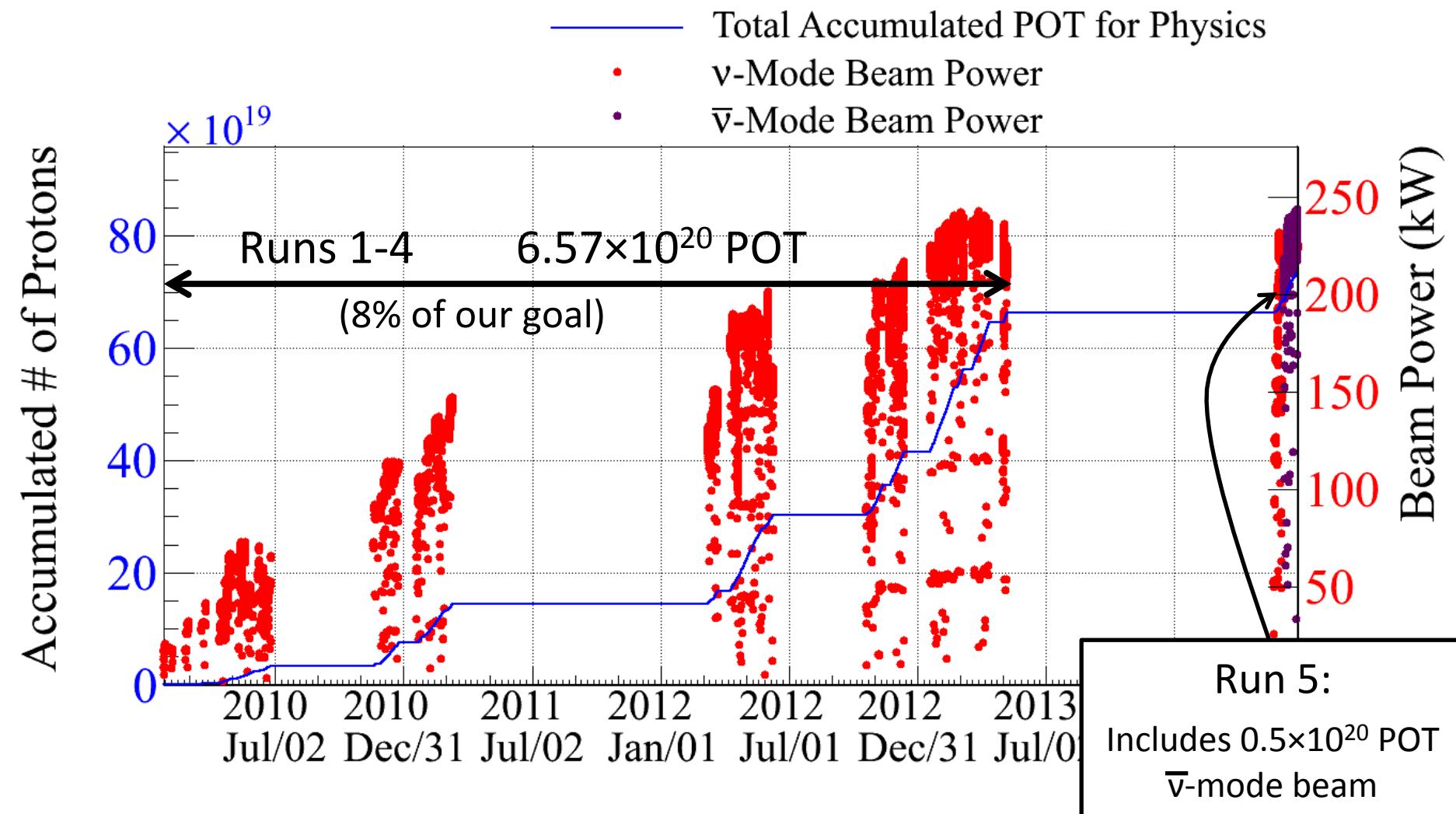


2.5° off-axis angle

- Peak at the atmospheric oscillation minimum
- Fewer backgrounds from high energy tail

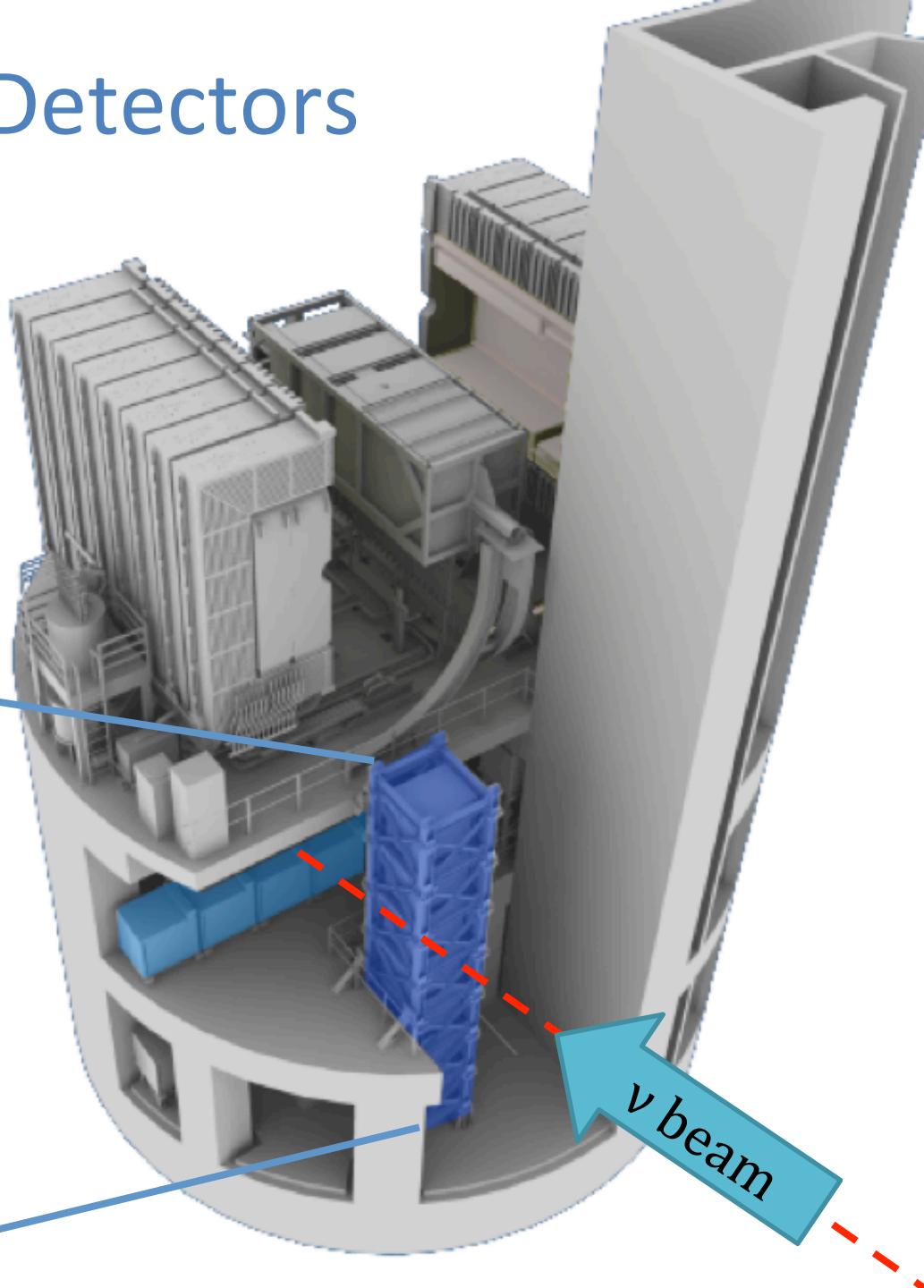


Accumulated POT

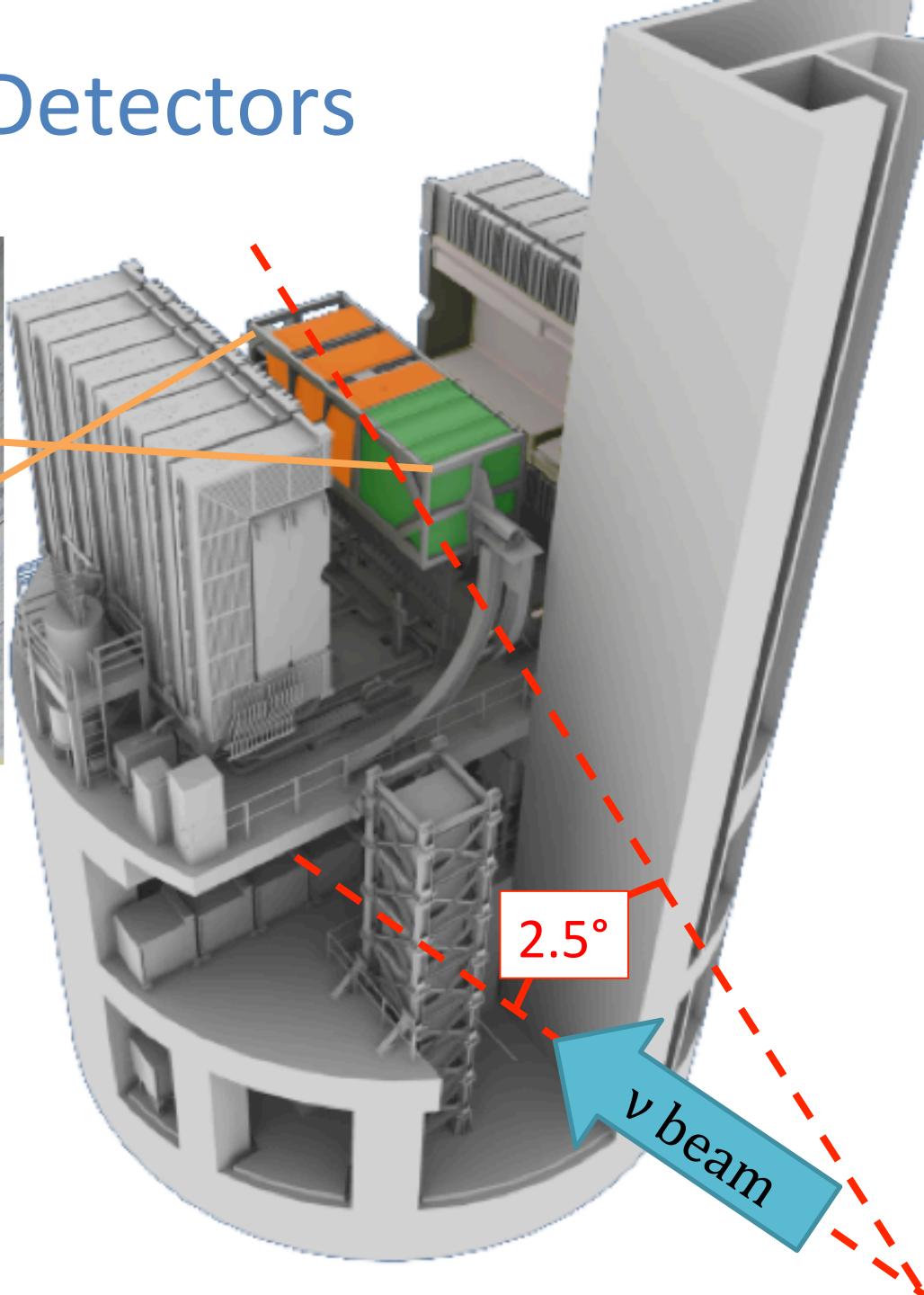
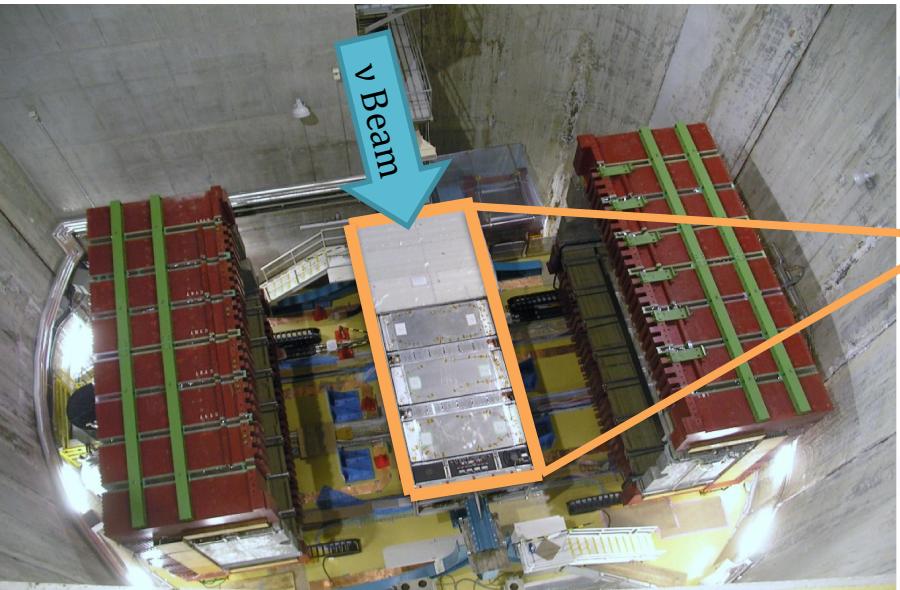


Near Detectors

- INGRID
 - On-axis
 - Beam monitoring



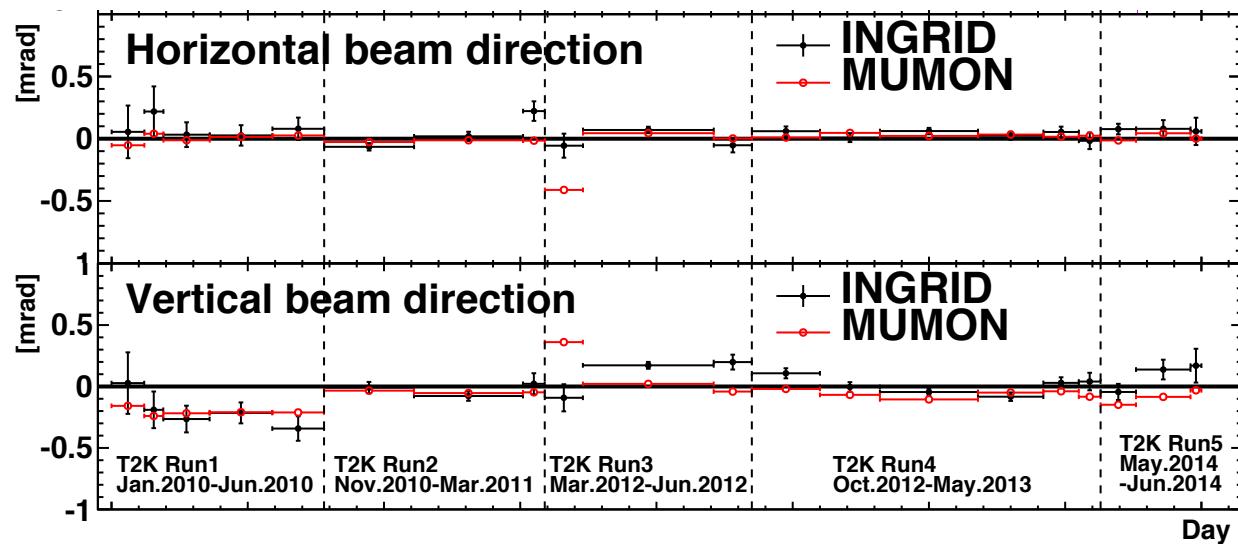
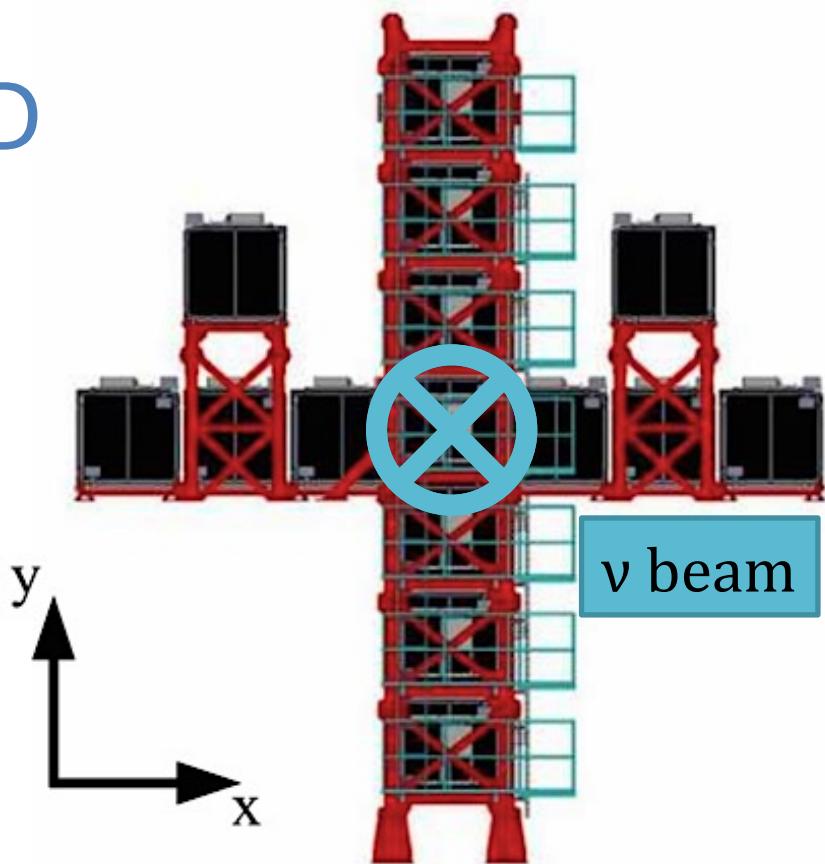
Near Detectors



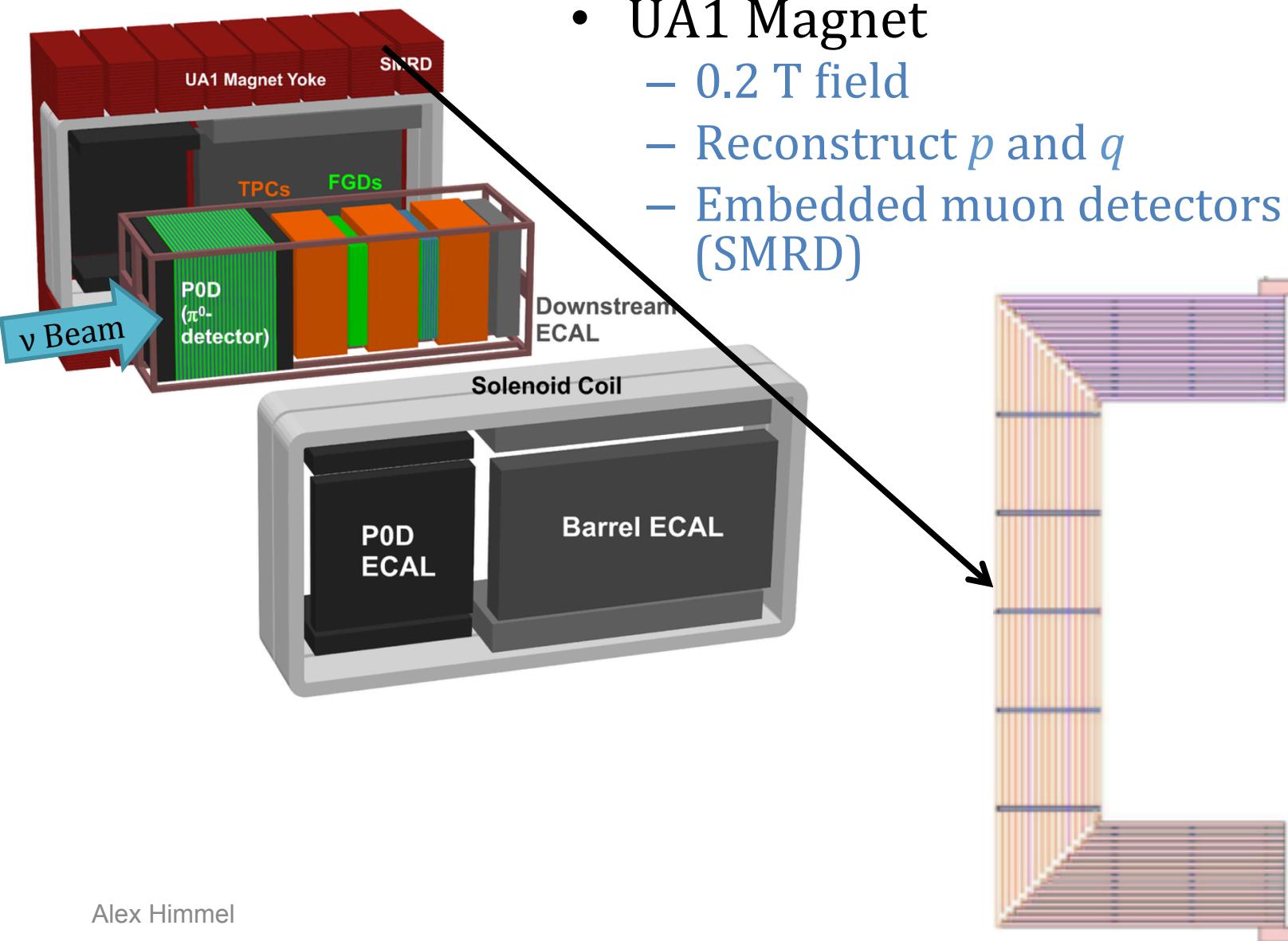
- ND280
 - 2.5° off-axis
 - Measure spectrum and composition before oscillations

INGRID

- Alternating planes of iron and plastic scintillator
- Measures beam intensity and direction over time.

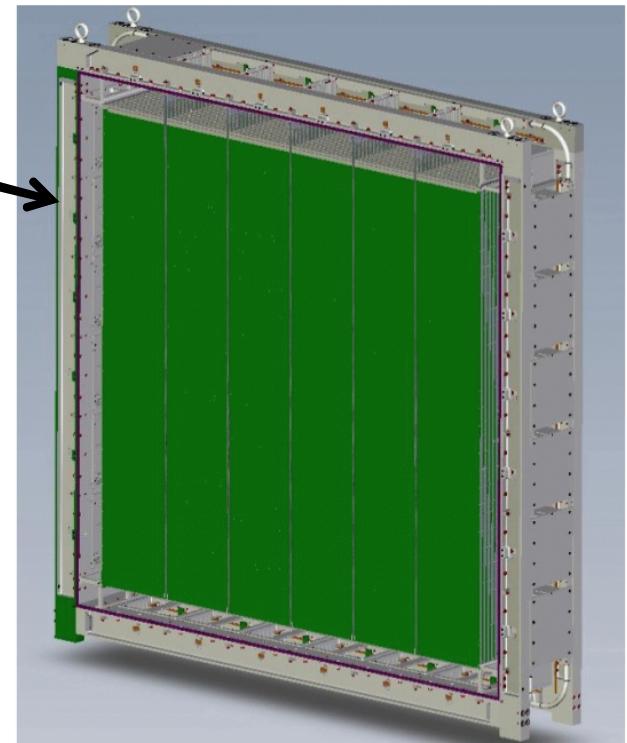
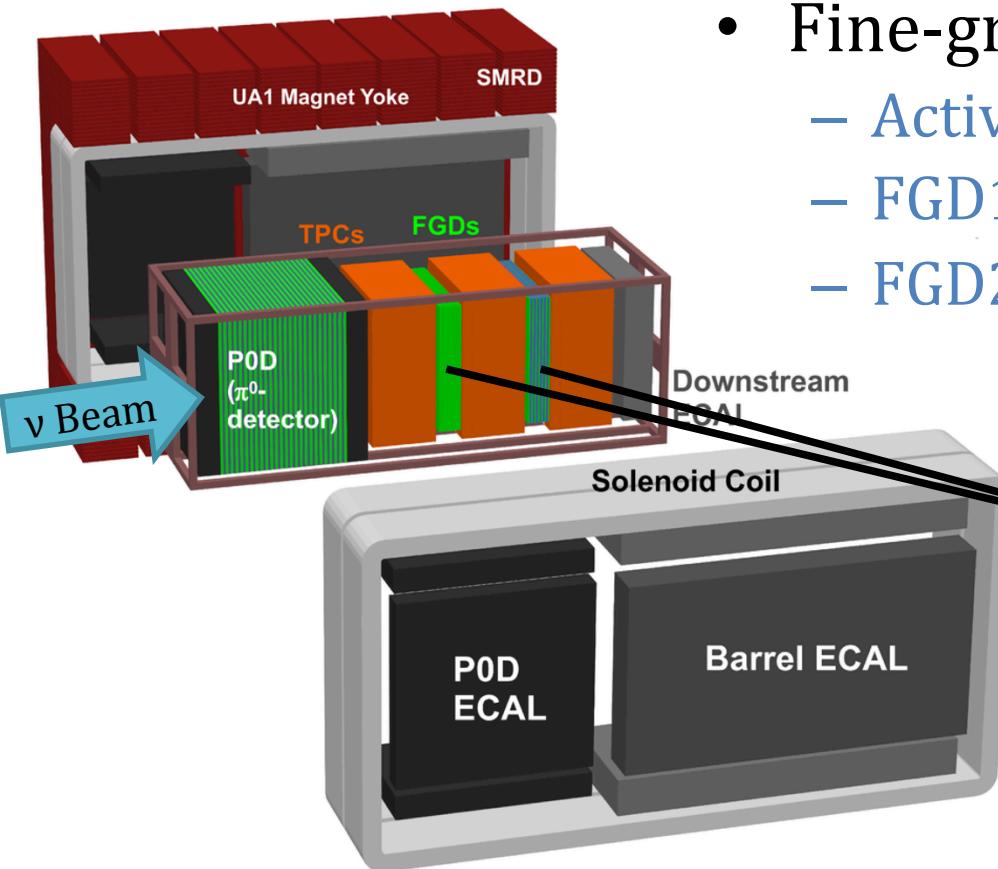


ND280 Detector Components



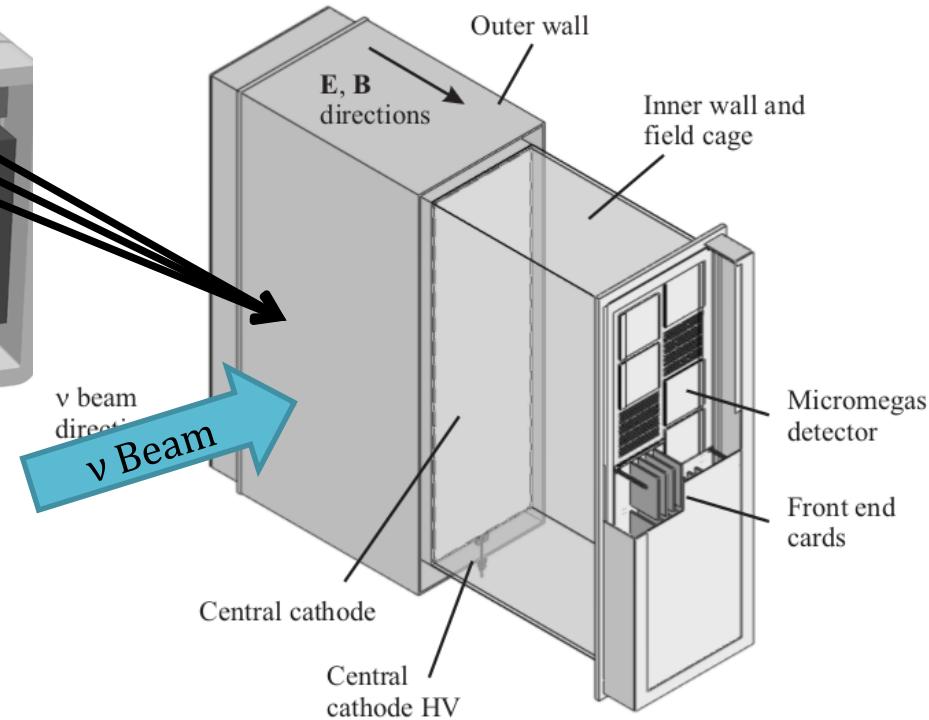
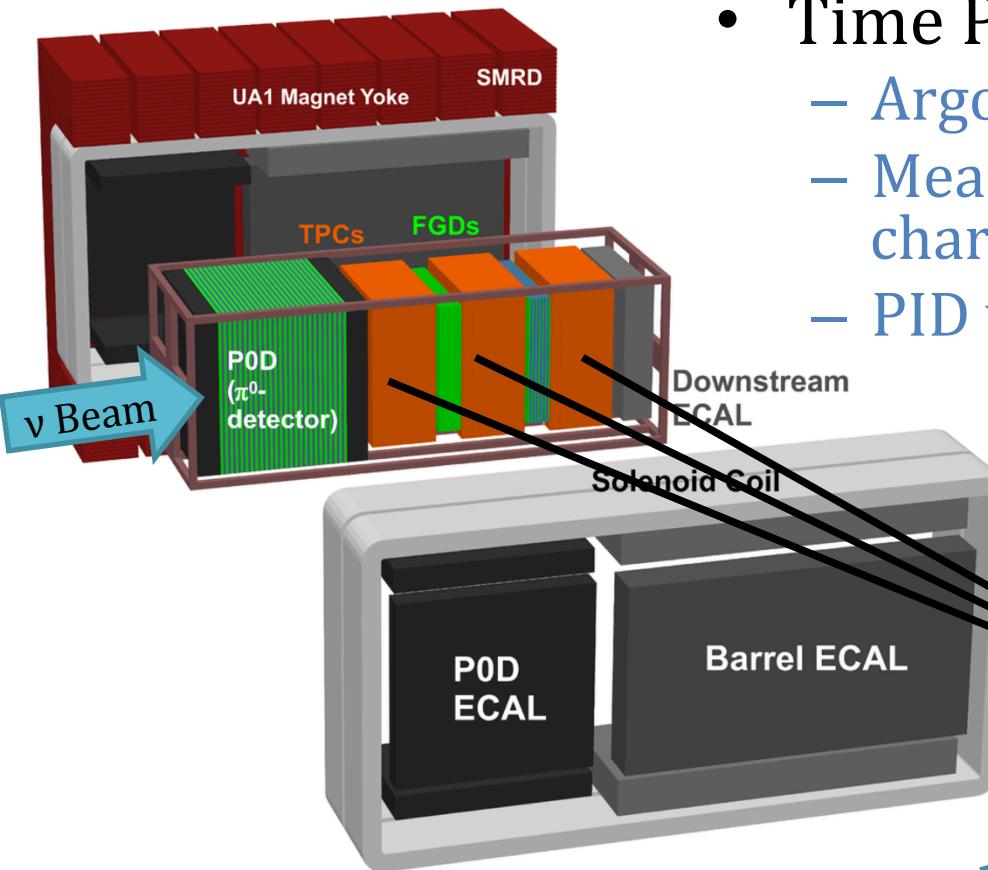
ND280 Detector Components

- Fine-grained detectors (FGDs)
 - Active neutrino interaction targets
 - FGD1 – scintillator (Carbon)
 - FGD2 – scintillator and water



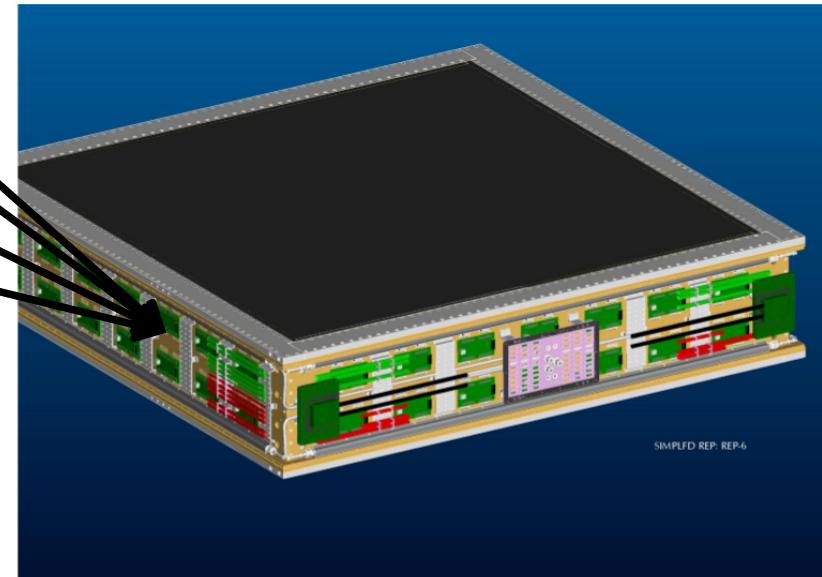
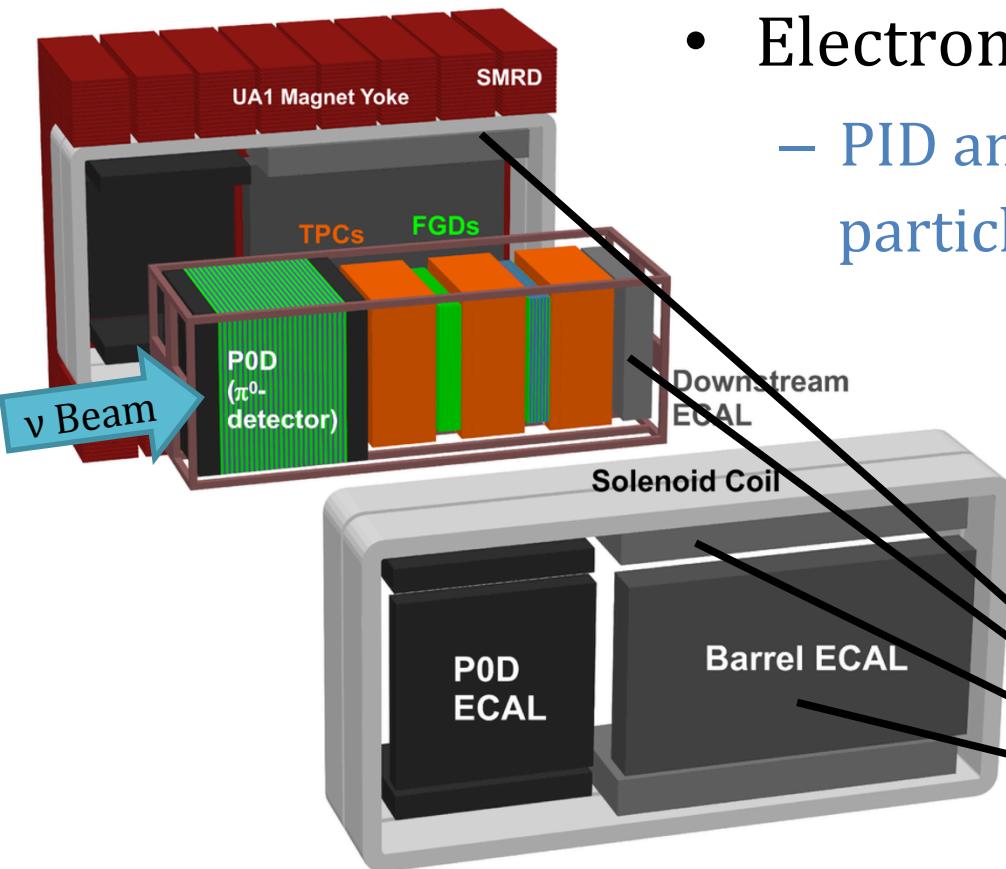
ND280 Detector Components

- Time Projection Chambers (TPCs)
 - Argon gas detectors
 - Measure p (10% @1 GeV) and charge sign
 - PID with good e/μ separation

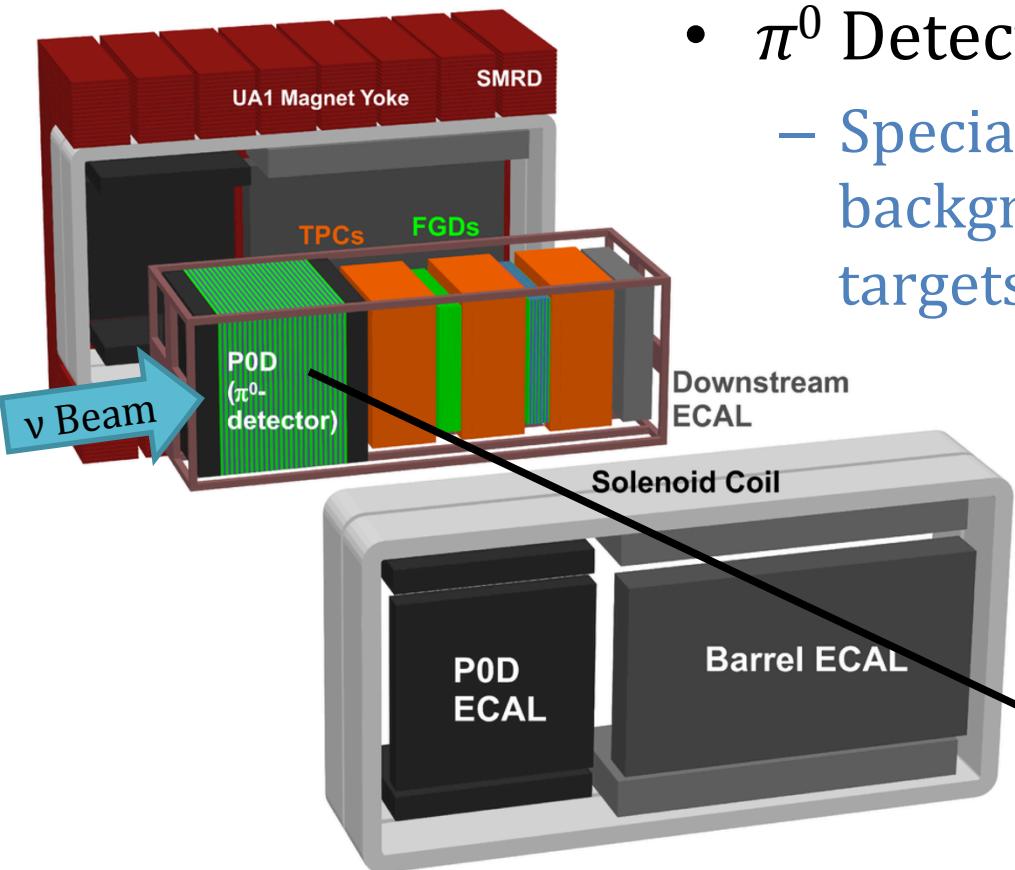


ND280 Detector Components

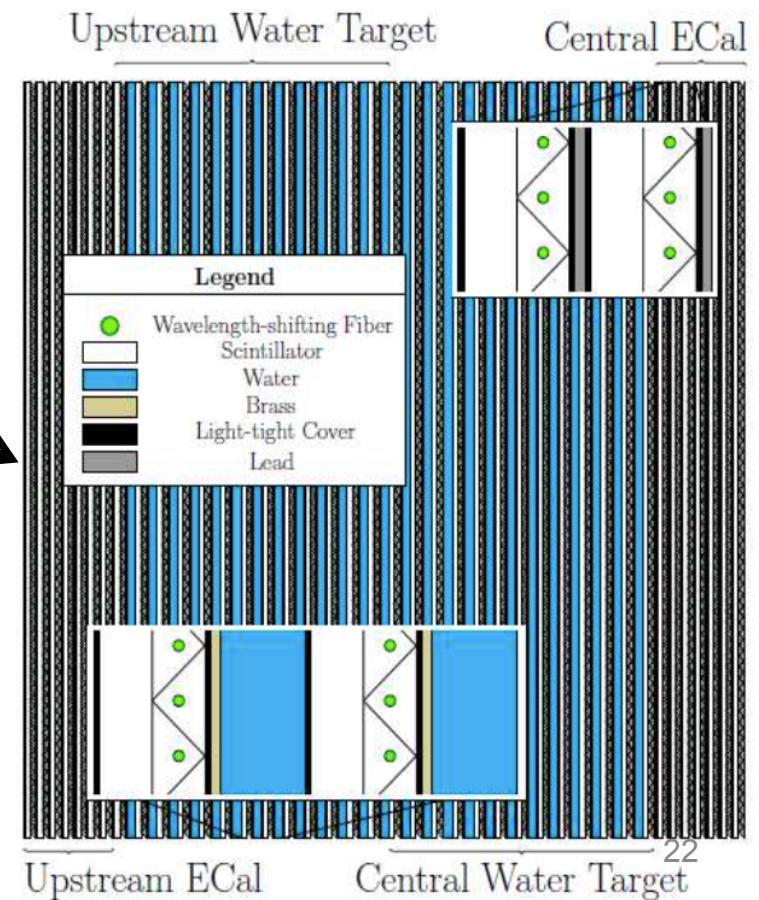
- Electromagnetic Calorimeters (Ecals)
 - PID and Reconstruction for exiting particles



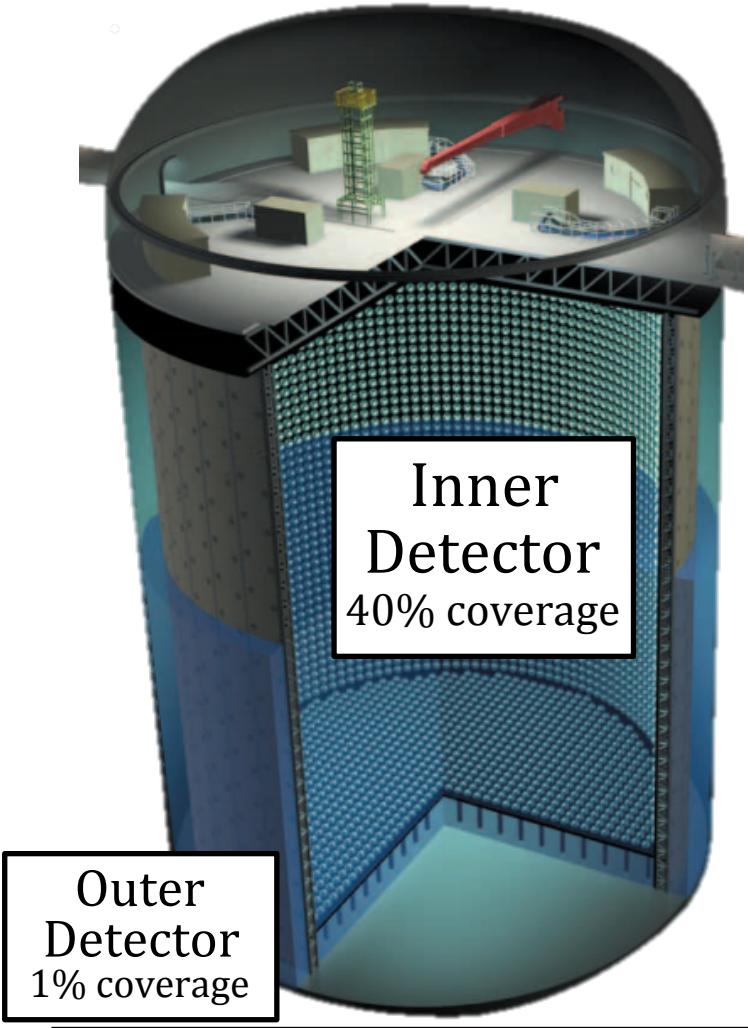
ND280 Detector Components



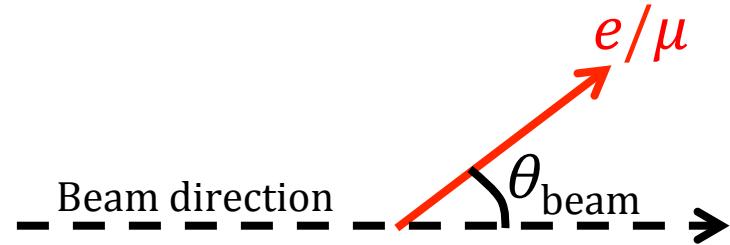
- π^0 Detector (P0D)
 - Specialized detector for NC π^0 backgrounds with removable water targets



SK Detector



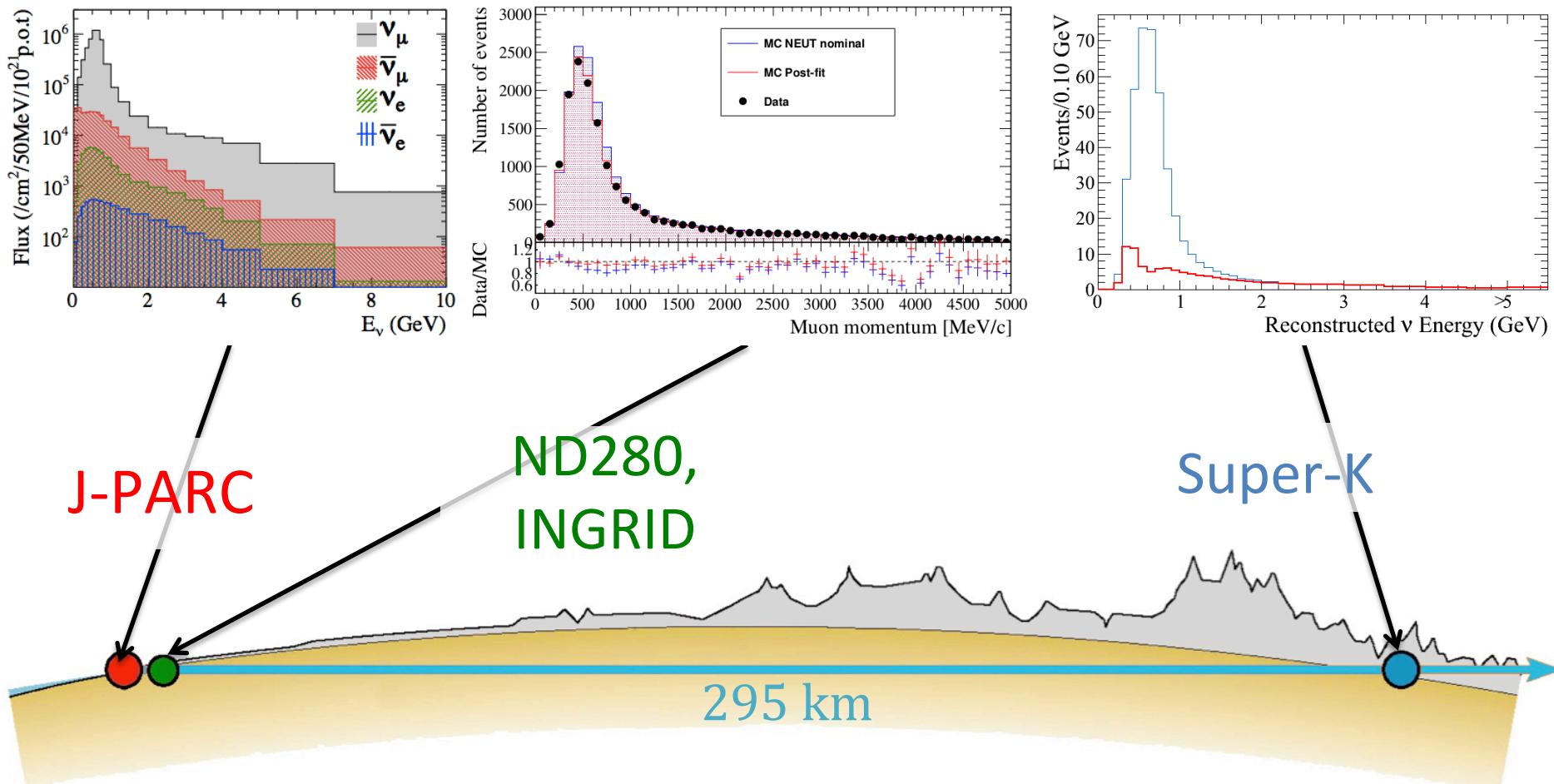
- 50 ktonne (22.5 ktonne fiducial) water Cherenkov detector
- 1 km underneath Ikenoyama, near Kamioka, Japan
- Can reconstruct neutrino energy with CCQE kinematics
 - Reco. p and θ from beam



$$E_\nu = \frac{m_p^2 - m_{n'}^2 - m_\ell^2 + 2m_{n'}^2 E_\ell}{2(m_{n'} - E_\ell + p_\ell \cos \theta_{\text{beam}})}$$

$$\ell = e^\pm, \mu^\pm \quad m_{n'} = m_n - E_b$$

Long-baseline Analyses



Long-baseline Analyses

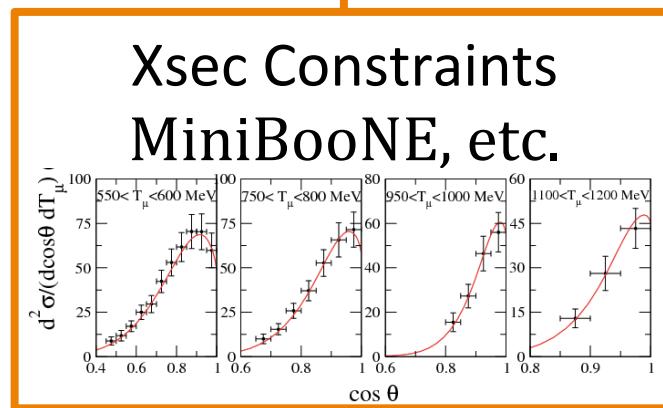
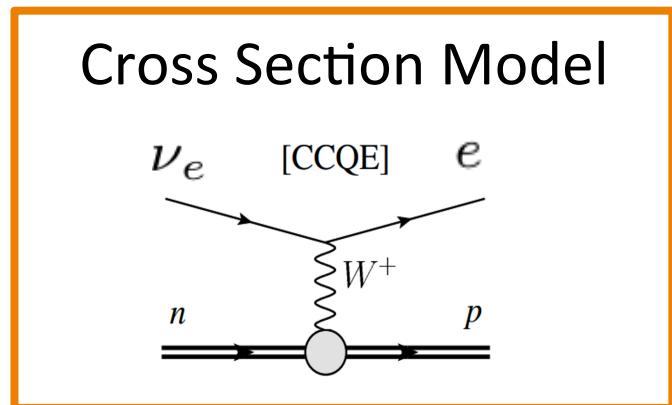
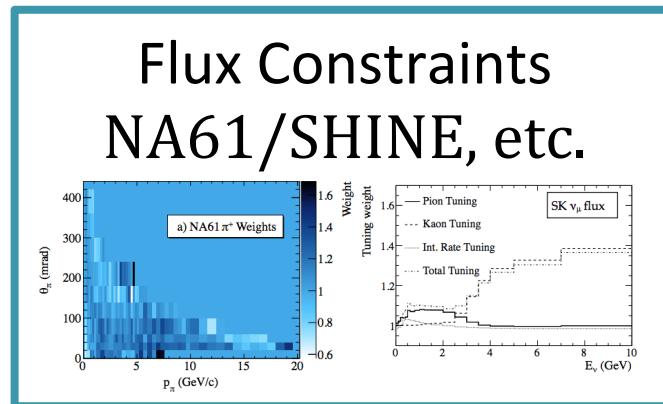
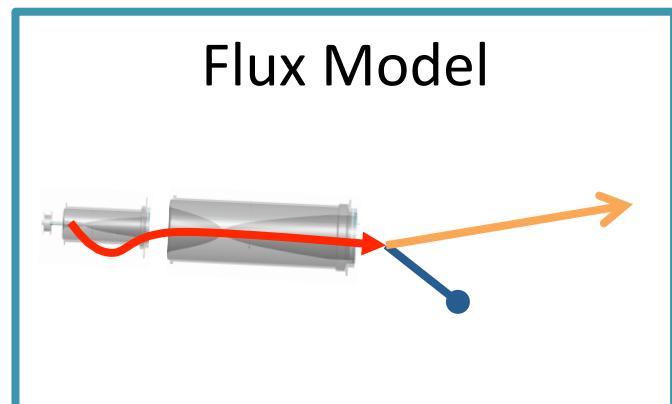
- Use ν_μ data from the near detectors to predict the spectrum at SK without oscillations
- Compare with SK ν_μ data:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \left(\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 \theta_{23} \sin^2 2\theta_{13} \right) \sin^2 \left(\frac{\Delta m^2 L}{4E_\nu} \right)$$

- Compare with SK ν_e data:

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \approx & \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E_\nu} \right) \left(1 + \frac{4\sqrt{2}G_F n_e E}{\Delta m_{31}^2} (1 - 2 \sin^2 \theta_{13}) \right) \\ & - \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E_\nu} \right) \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) \end{aligned}$$

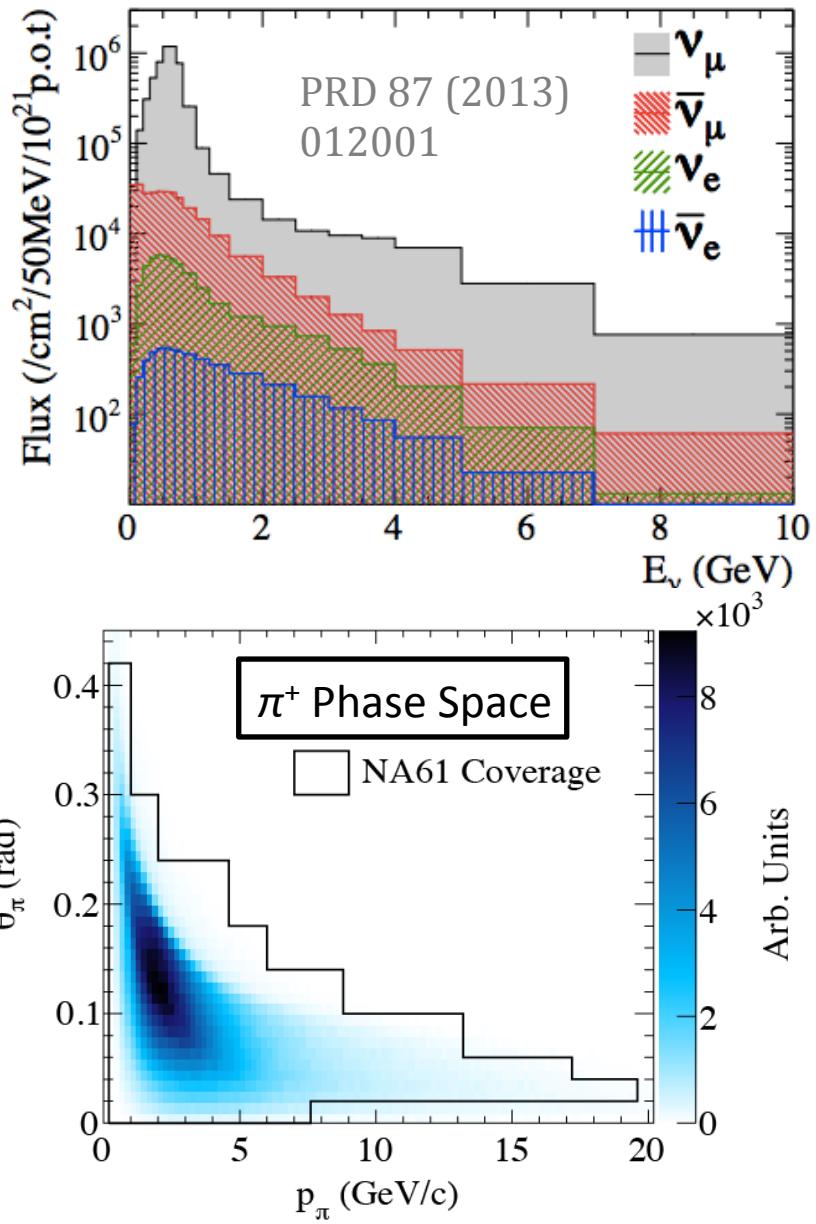
Predicting the SK Spectrum



Beam Modeling and Constraint

- Simulate the beam with:
 - Fluka in target, Geant3 in beamline
- Components:

93% ν_μ	6% $\bar{\nu}_\mu$
1% ν_e	0.1% $\bar{\nu}_e$
- Reweight hadronic interactions and π/K production with external data
 - Reweight in target (C) and horns (Al)
 - Primary source is NA61/SHINE at CERN
 - Same beam energy and carbon target
 - Other sources for aluminum interactions



[1] N. Abgrall *et al.* (NA61/SHINE Collaboration), Phys. Rev. C 84, 034604 (2011)

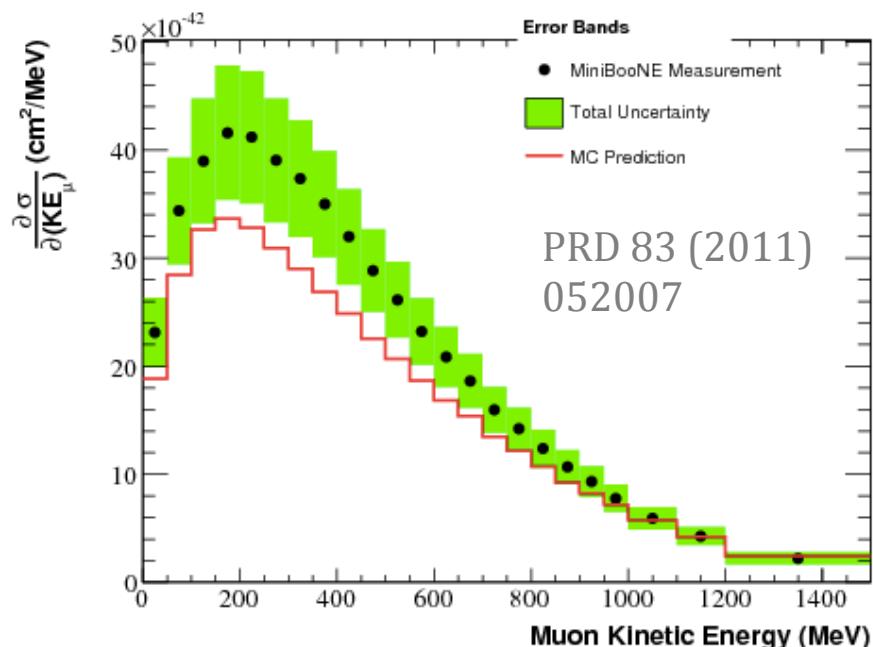
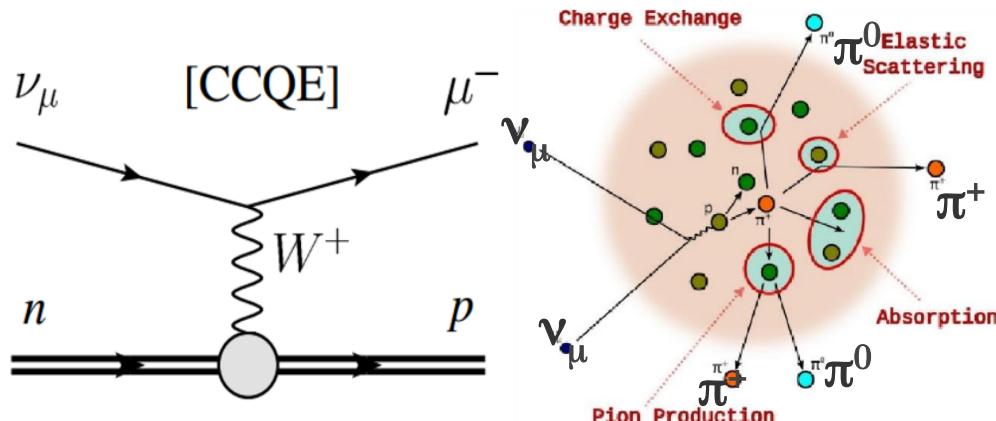
[2] N. Abgrall *et al.* (NA61/SHINE Collaboration), Phys. Rev. C 85, 035210 (2012)

[3] T. Eichten *et al.*, Nucl. Phys. B 44 (1972)

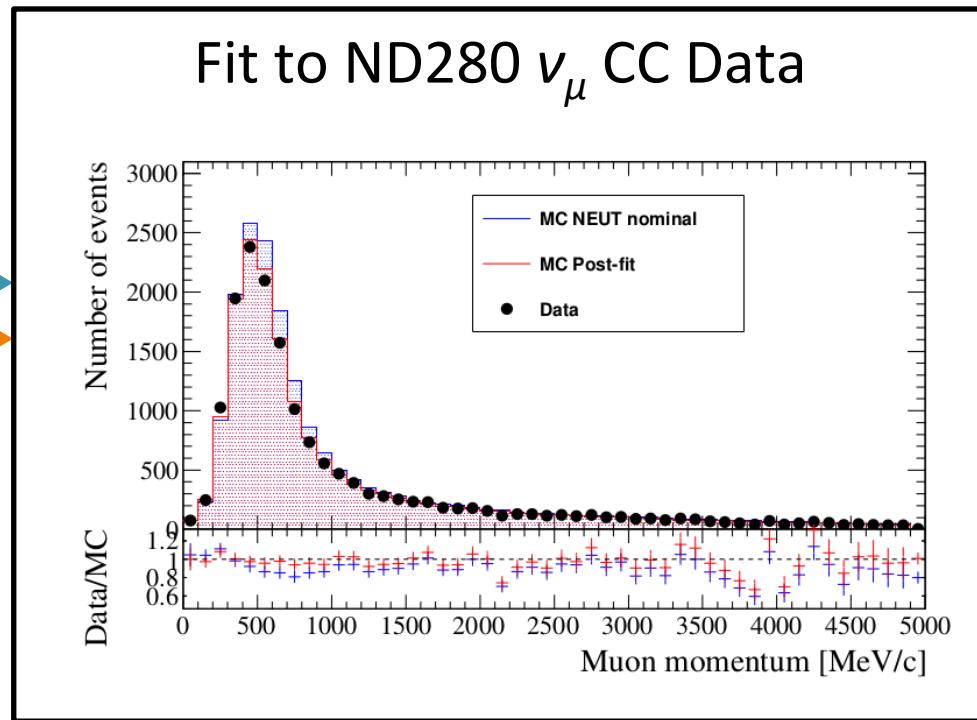
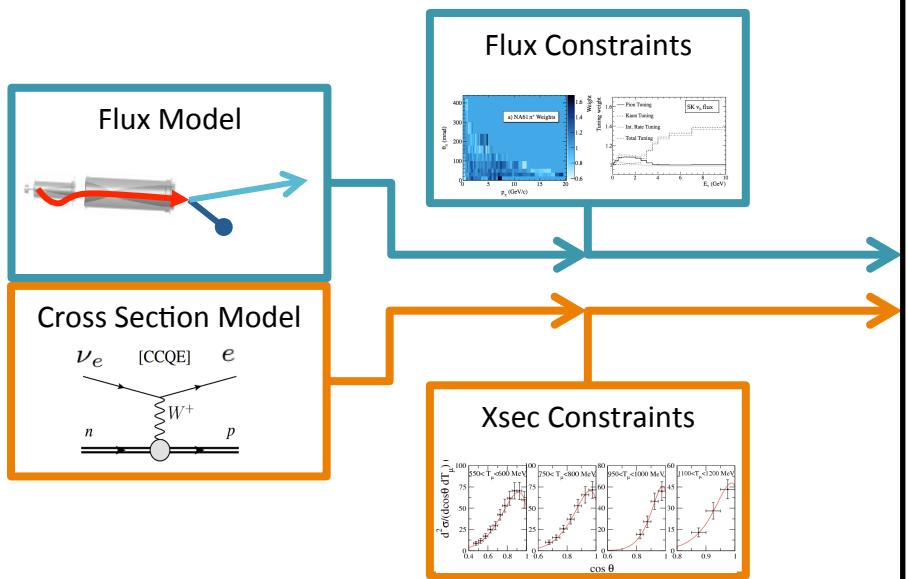
[4] J. V. Allaby *et al.*, Tech. Rep. 70-12 (CERN, 1970)

Cross Section Simulation and Constraints

- NEUT simulation (2012)
 - Initial interaction
 - CCQE, resonant- π , etc.
 - Final State nuclear effects
 - charge exchange, π absorption, etc.
- Parameterize models
 - Some model parameters like M_A , p_F , E_b
 - Some energy-dependent normalizations
- Tune model parameters to external neutrino data
 - Primarily MiniBooNE



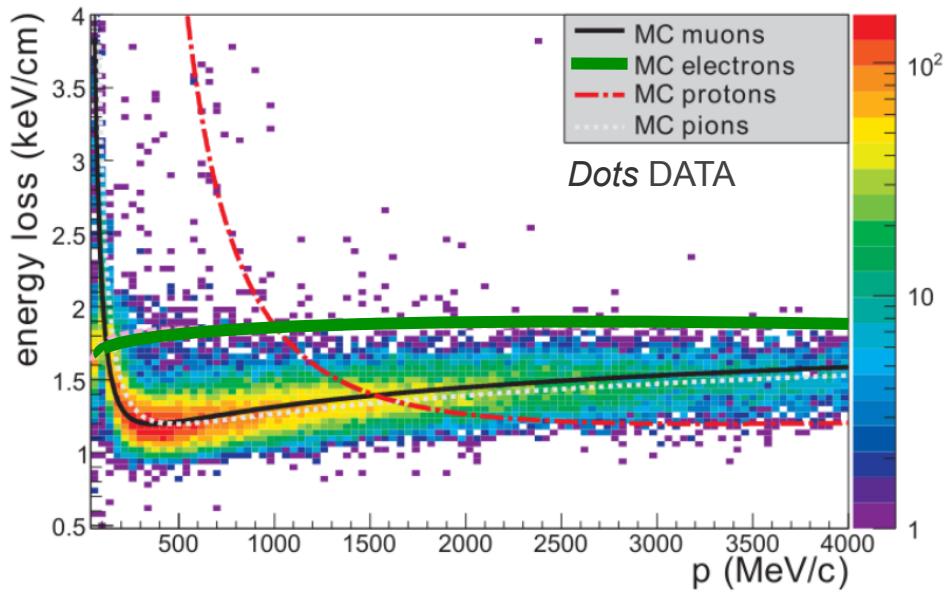
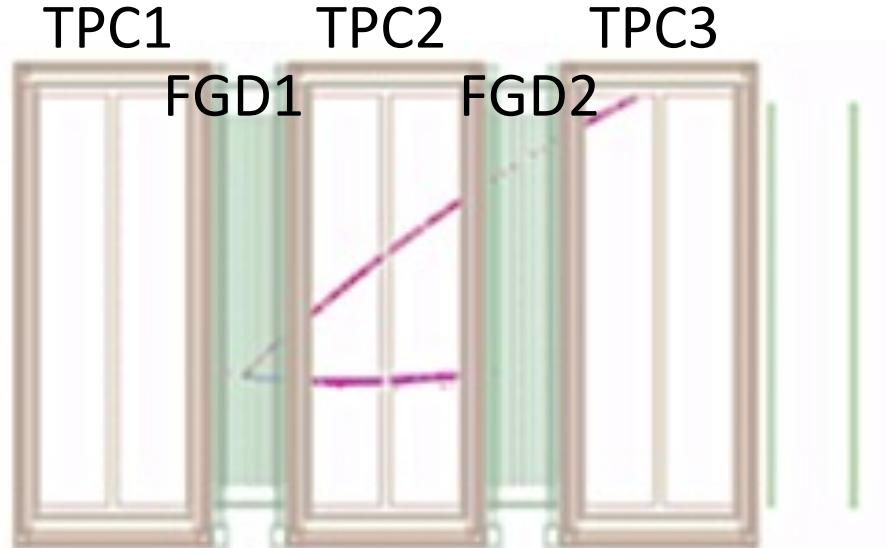
Predicting the SK Spectrum



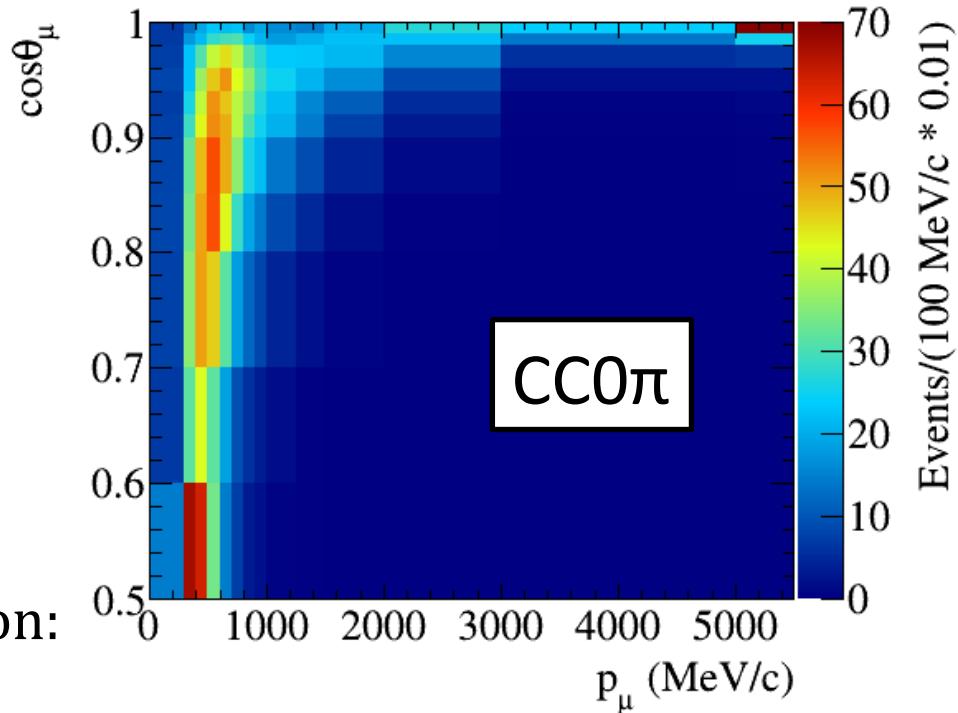
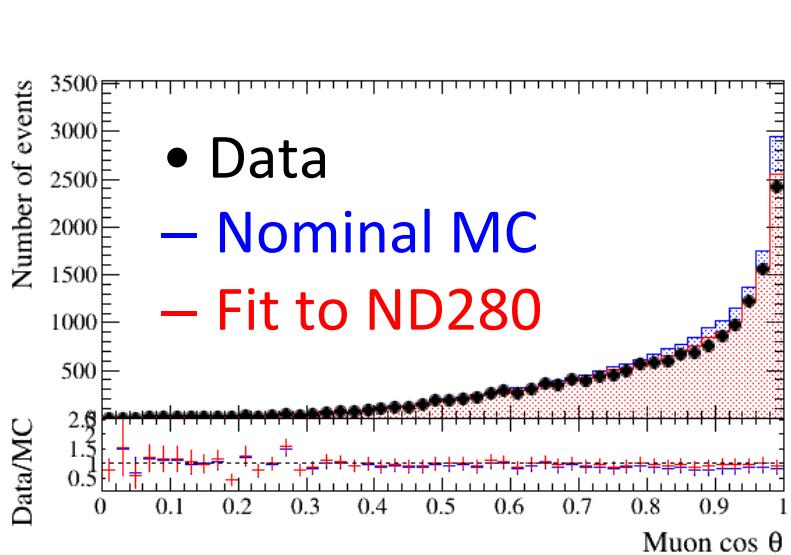
Selecting CC ν_μ in ND280

- Require a μ^- track starting in FGD1
- PID based on:
 - dE/dx in TPC
 - Ecal cluster geometry (shower vs. track)
- Divide into 3 sub-samples:

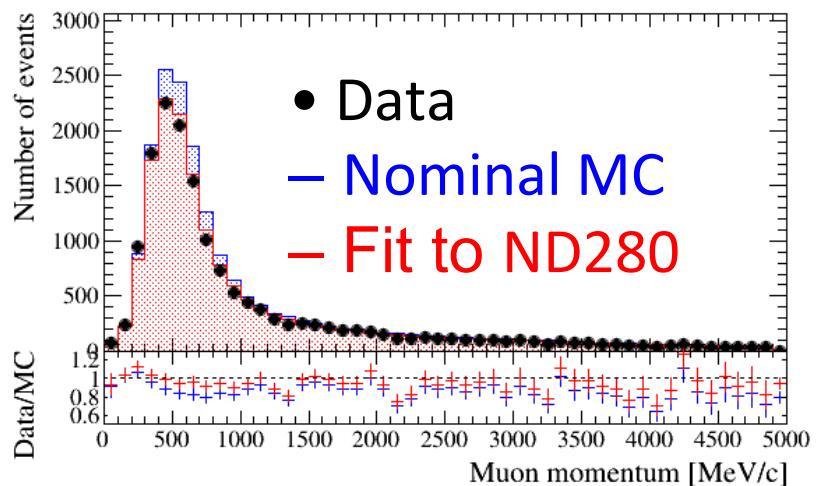
Purity	
CC0 π	73%
CC1 π^+	49%
CC other	74%



ND280 Fit to Constrain Systematics

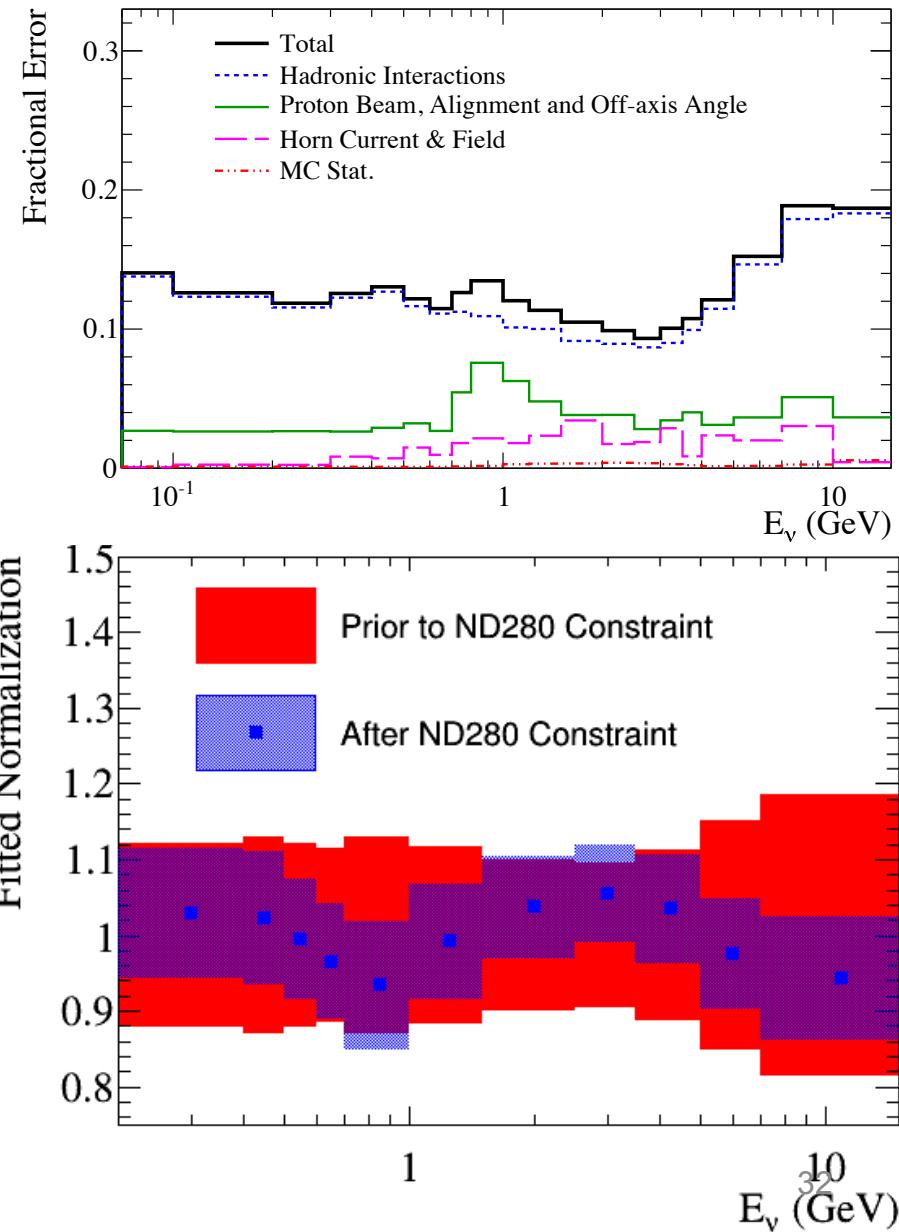


- Fit each sub-sample in 2 dimension:
 - μ^- momentum and angle
- All parameters in fit are systematic errors
 - Flux, cross sections, detector errors
 - No ND ν_μ oscillations



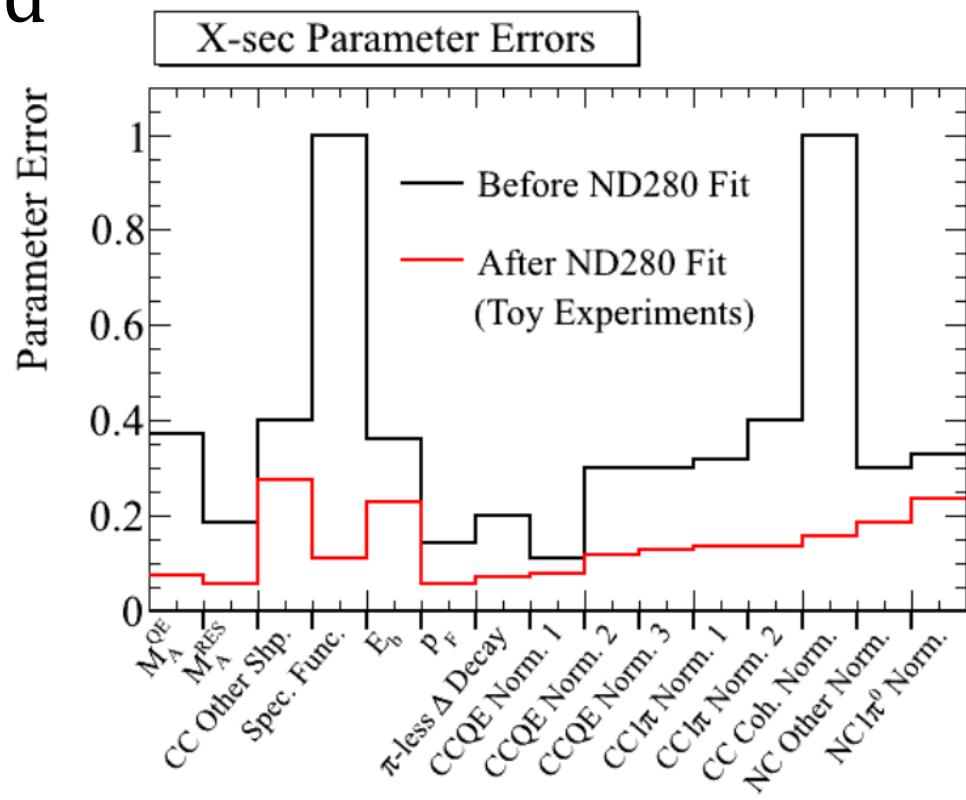
Flux Systematic Uncertainties

- 10-15% error on flux w/ external data
 - Hadron production
 - Beam alignment
- After fit to ν_μ CC data
 - Flux error alone goes from 12% \rightarrow 8% at osc. peak
 - Central values shifted to better fit the data

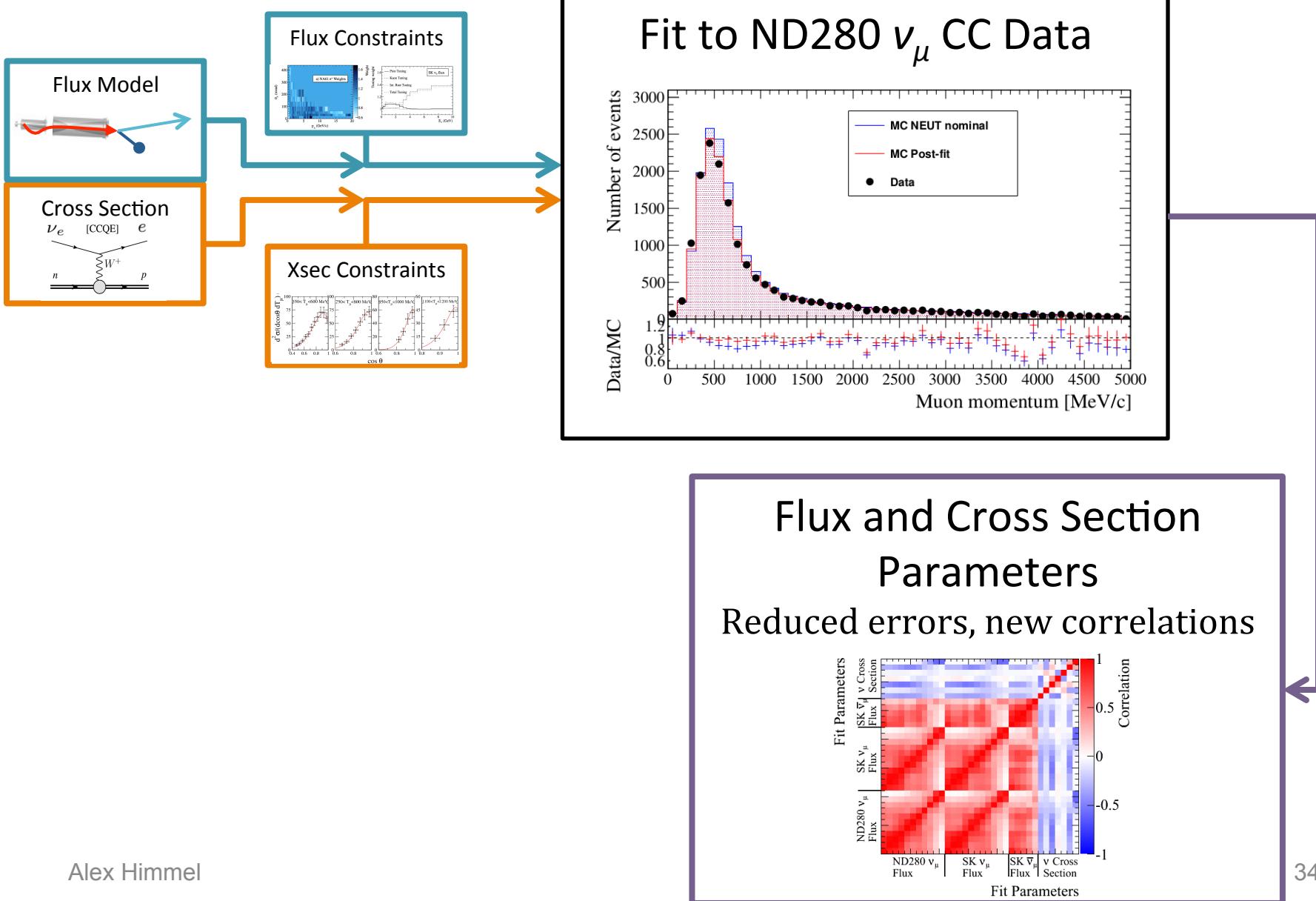


Cross Section Systematic Uncertainties

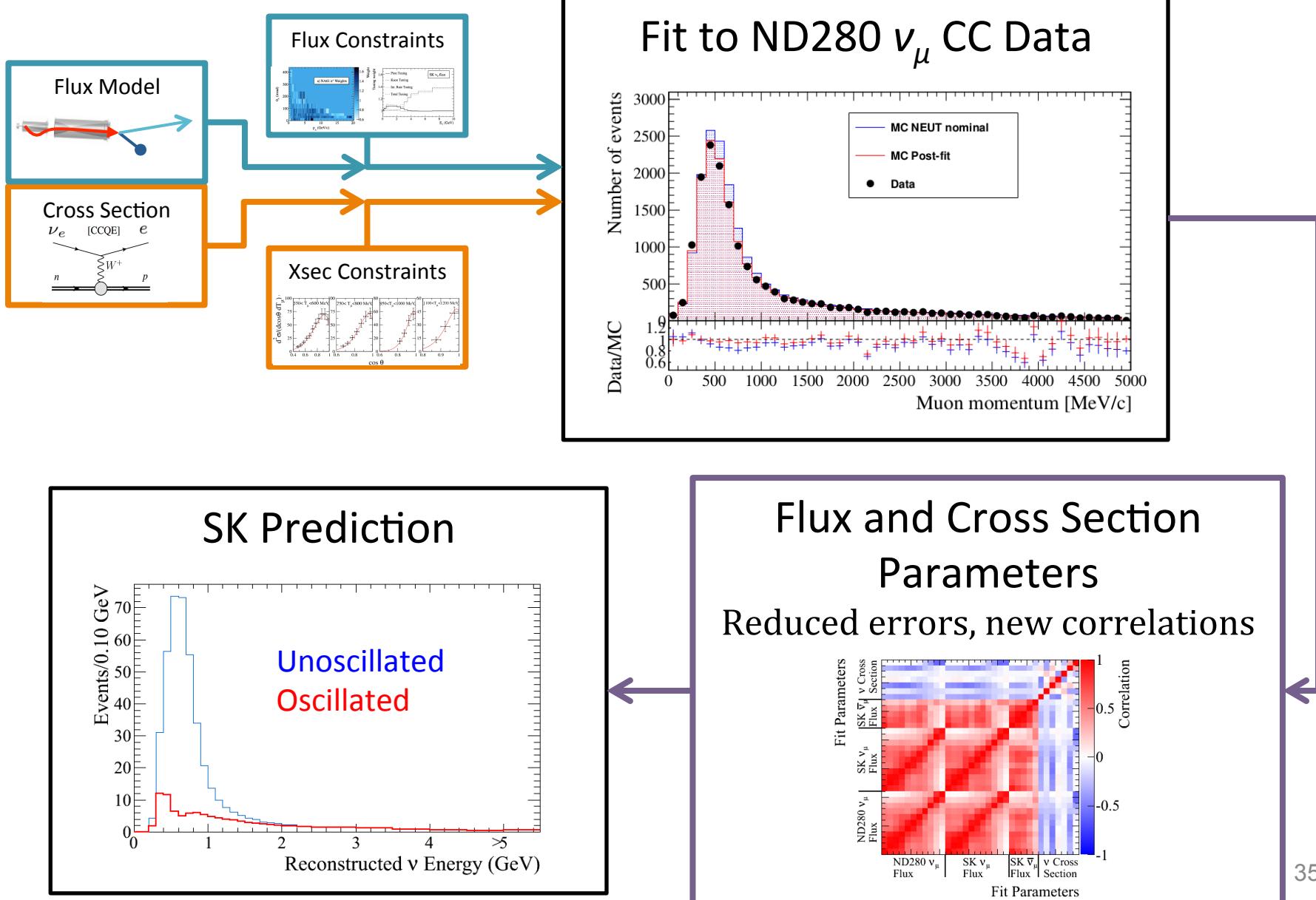
- Fit to ND280 ν_μ data reduces errors correlated between ND280 and SK
 - Reduced by a factor of 2 or more
- Not constrained:
 - 52% W-shape
 - 3% $\sigma(\nu_e)/\sigma(\nu_\mu)$
 - 40% $\sigma(\bar{\nu})/\sigma(\nu)$
 - 30% out of fiducial volume
 - 4% Final state interactions



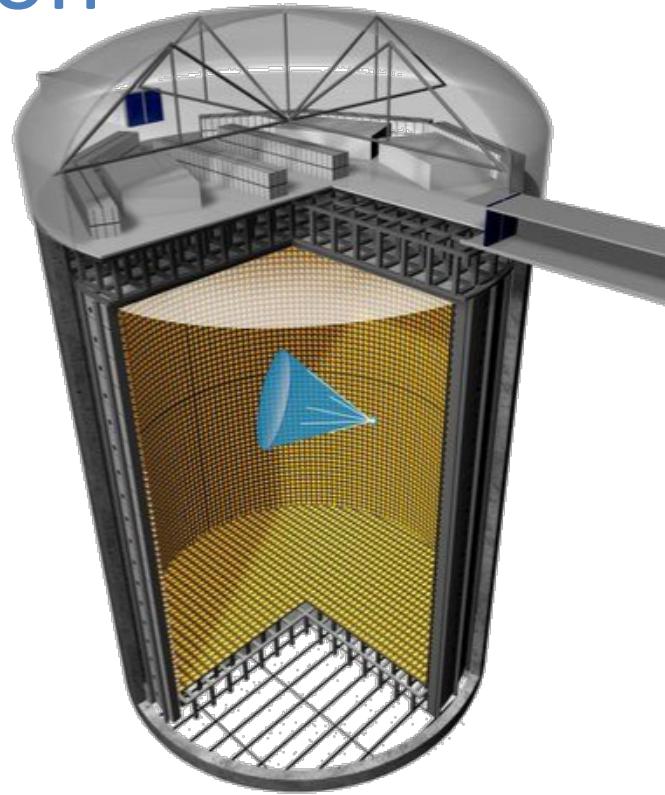
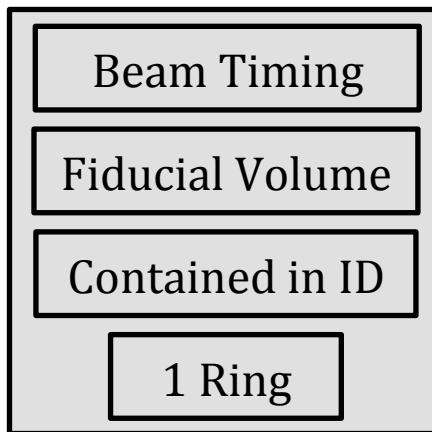
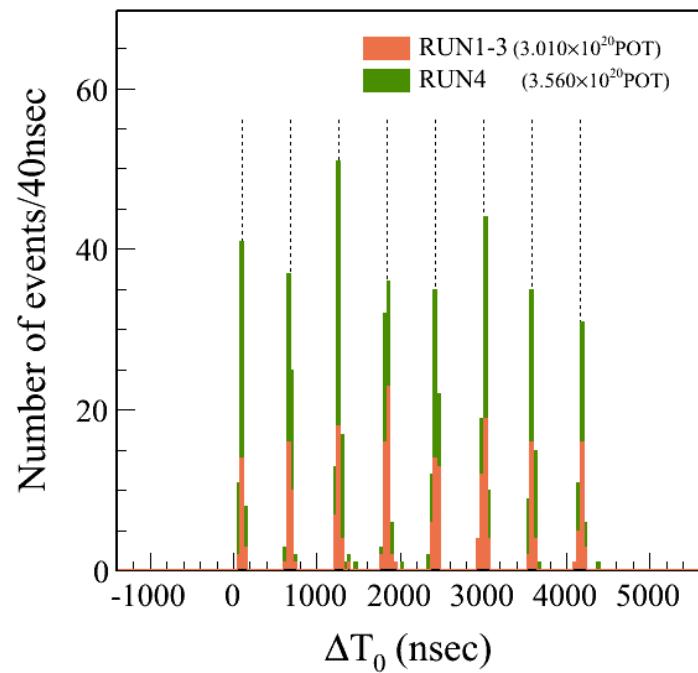
Predicting the SK Spectrum



Predicting the SK Spectrum

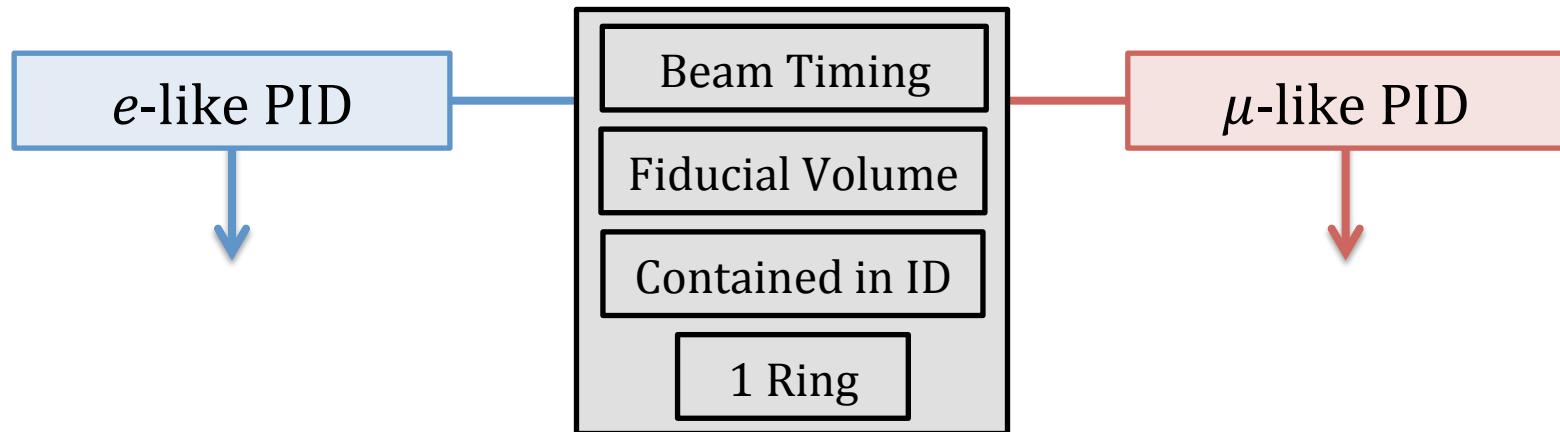


SK Event Selection

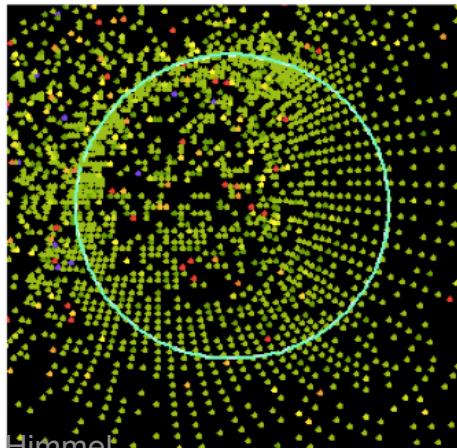


- Pre-selections exclude:
 - Non-beam events
 - Poorly reconstructed events
 - Non-QE events

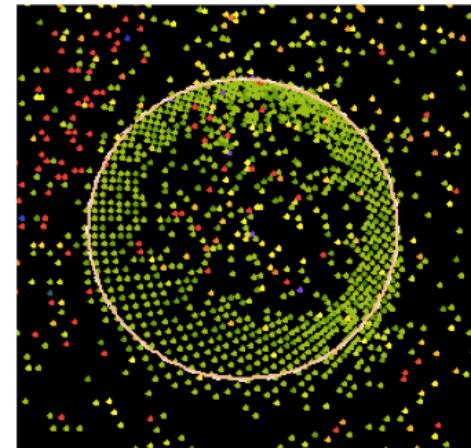
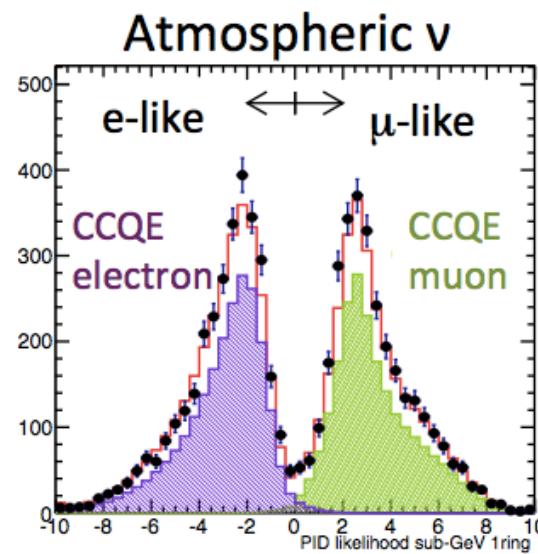
SK Event Selection



- e -like (e^\pm, γ)
 - scatter and shower
 - fuzzy edged ring
- μ -like (μ^\pm, π^\pm, p)
 - minimum-ionizing
 - sharp edged ring

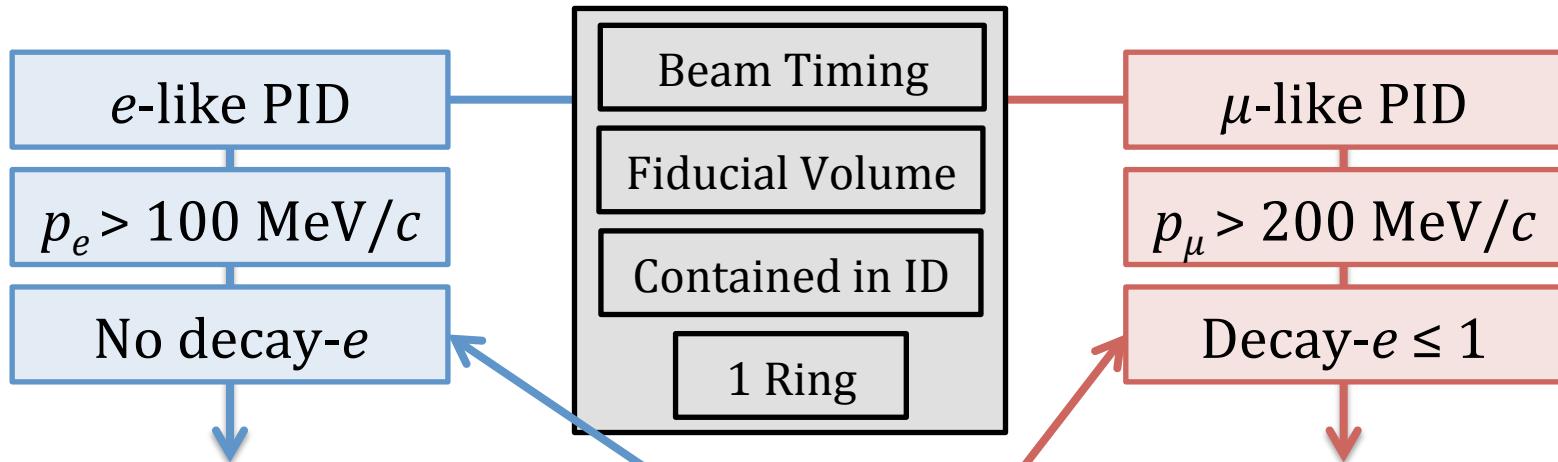


Alex Himmel

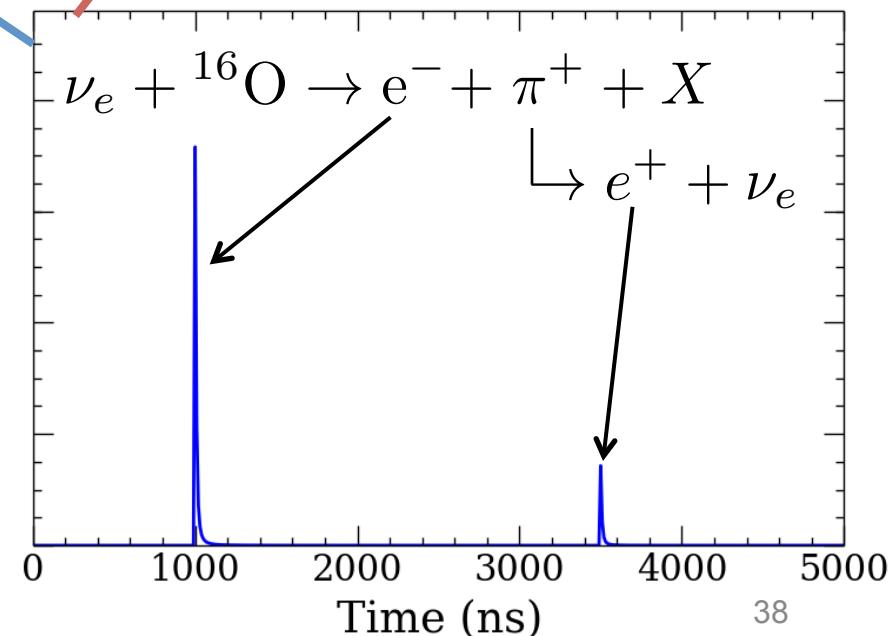


37

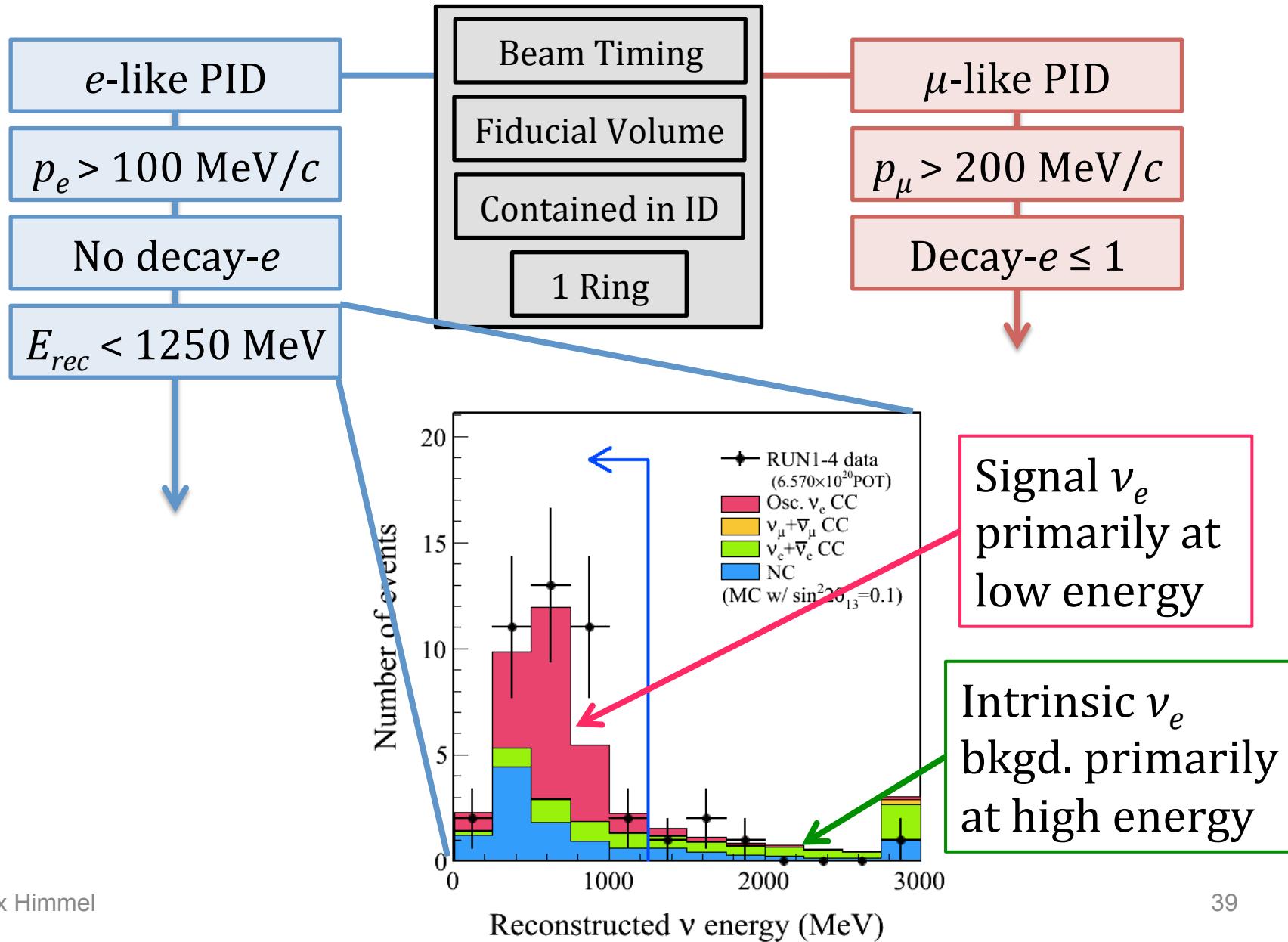
SK Event Selection



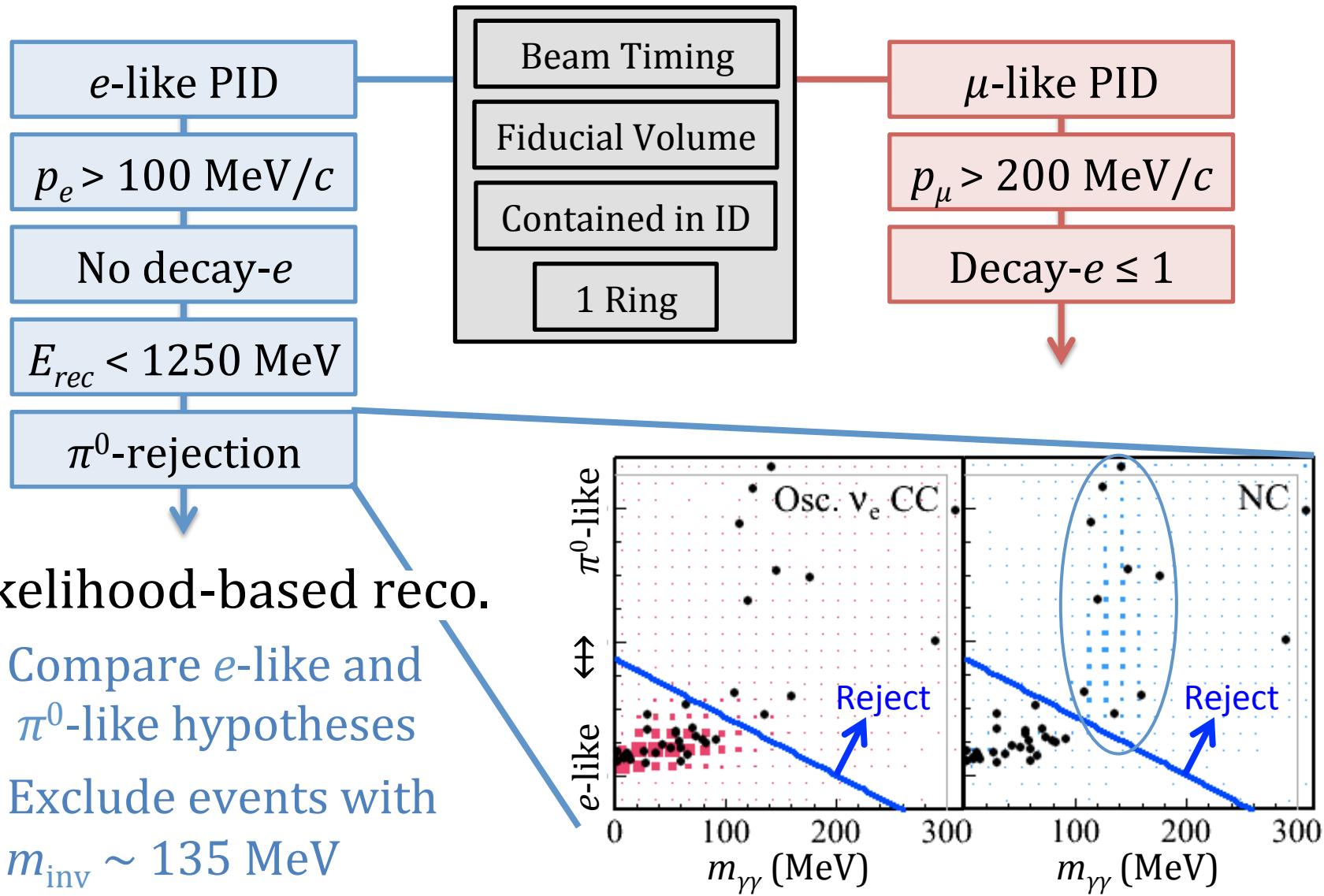
- Limit decay electrons to exclude events with invisible π^\pm 's
 - π^\pm Č threshold: 160 MeV
 - e^\pm Č threshold: 0.8 MeV



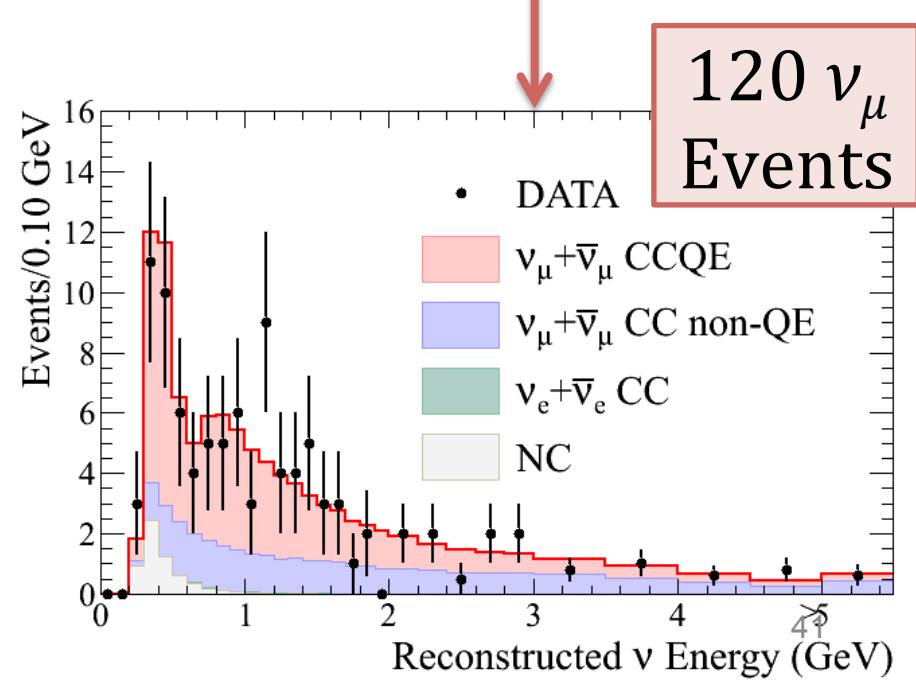
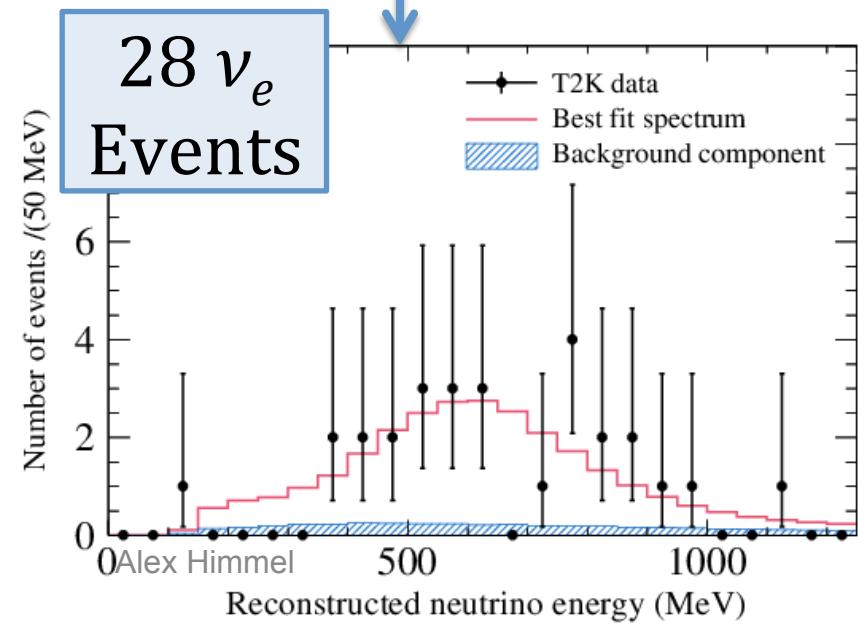
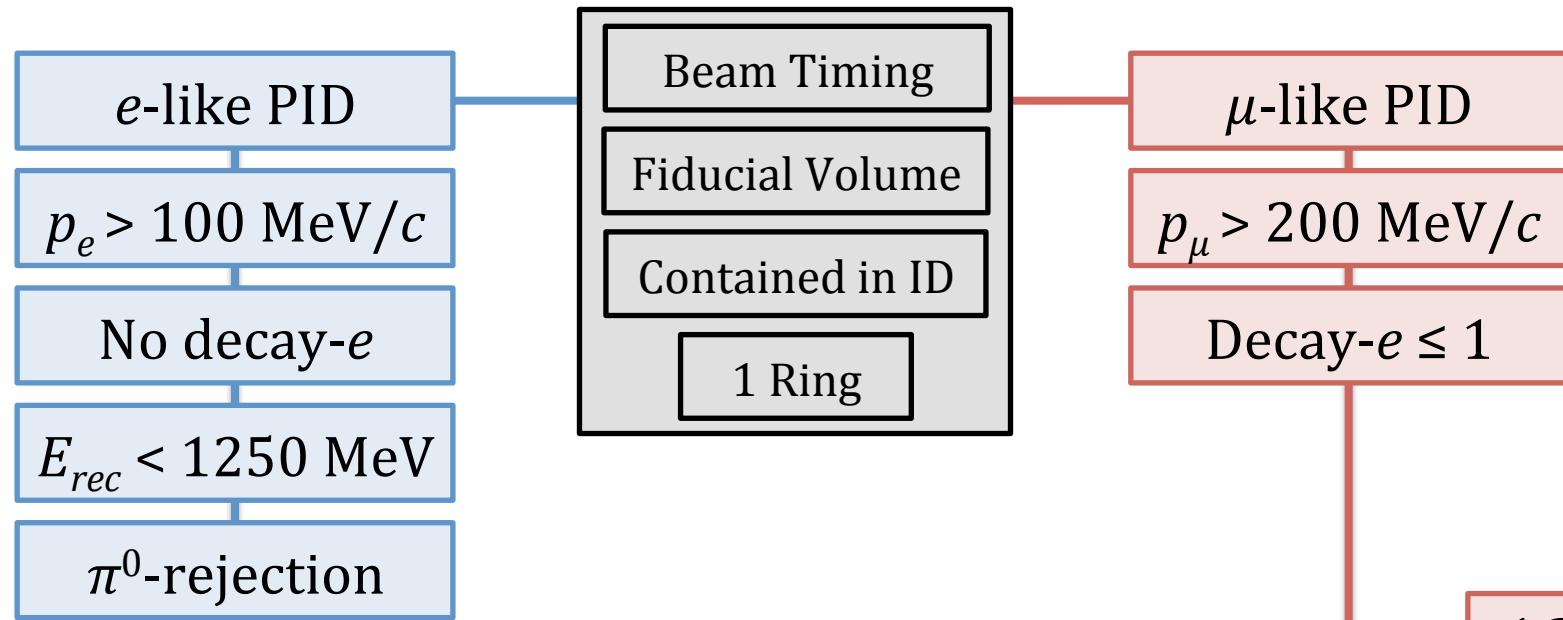
SK Event Selection



SK Event Selection



SK Event Selection



Systematic Uncertainties

ν_e Events		ν_μ Events	
ND280-constrained flux and cross section	3.1%	ND280-constrained flux and cross section	2.7%
Unconstrained cross section	4.7%	Unconstrained cross section	5.0%
SK detector efficiency	2.4%	SK detector efficiency	3.0%
Final or secondary hadronic interactions	2.7%	Final or secondary hadronic interactions	4.0%
Total	6.8%	Total	7.7%

Flux and cross section would be
 $> 20\%$ without ND280 constraint

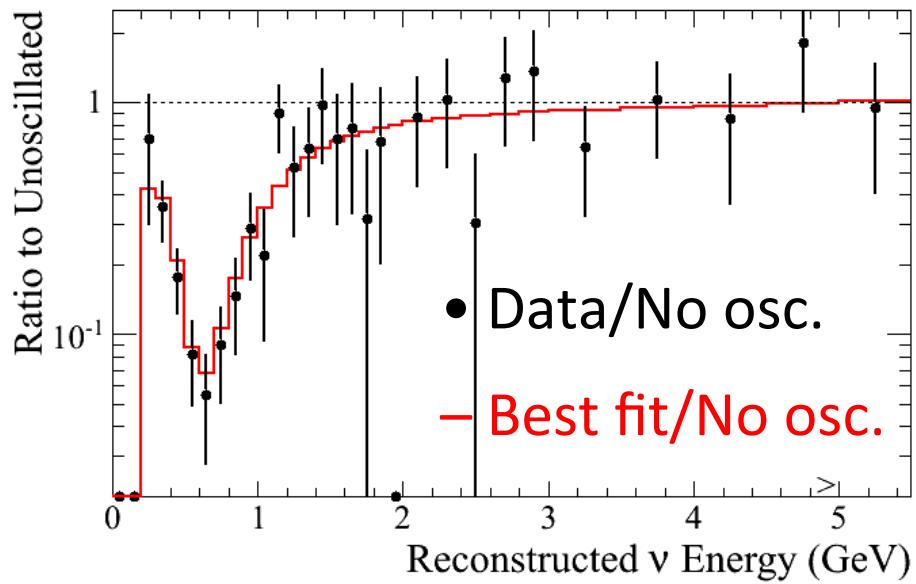
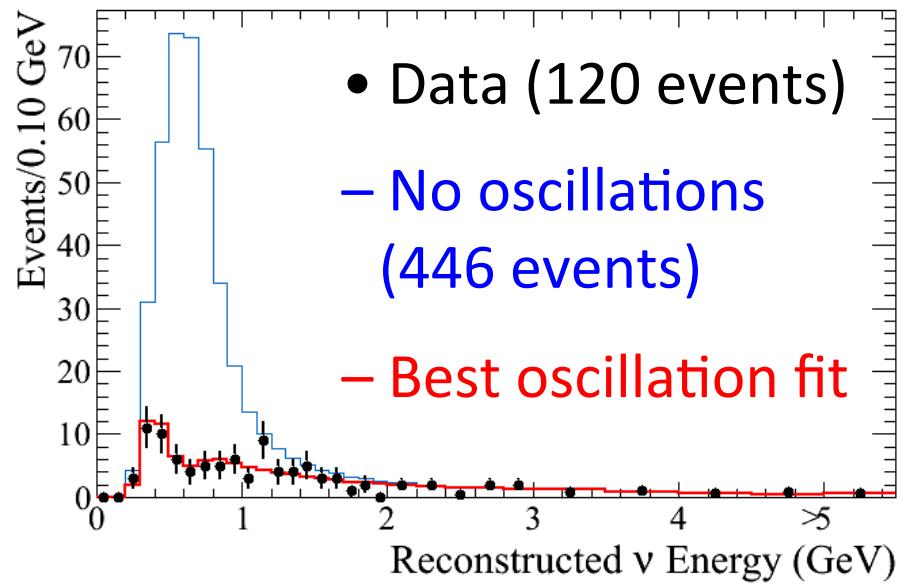
Fit for ν_μ Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \left(\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 \theta_{23} \sin^2 2\theta_{13} \right) \sin^2 \left(\frac{\Delta m^2 L}{4E_\nu} \right)$$

- Fit for $\sin^2 \theta_{23}$ and $\Delta m^2_{32}/\Delta m^2_{13}$ depending on mass hierarchy
- Take θ_{13} from reactor constraint
 - $\sin^2 \theta_{13} = 0.0251 \pm 0.0035$ at publication
 -  from the PDG, PRD86 010001 (2012, 2013 update)
- Maximal disappearance \neq maximal mixing

$$\sin^2 \theta_{23} = \frac{1/2}{\cos^2 \theta_{13}} = 0.513$$

Fit for ν_μ Disappearance



Normal Hierarchy

$$\sin^2 \theta_{23} = 0.514^{+0.055}_{-0.056}$$

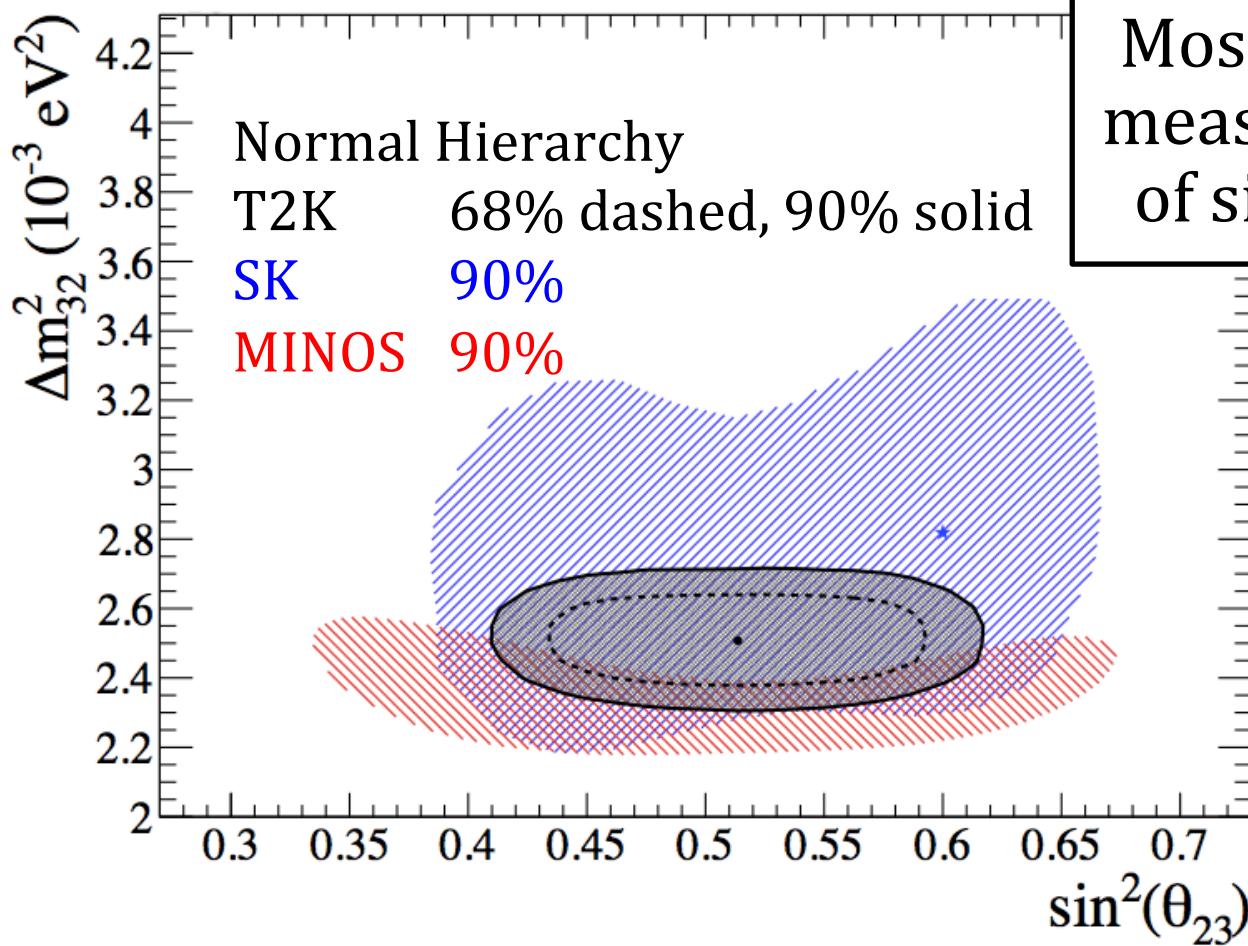
$$\Delta m_{32}^2 = (2.51 \pm 0.10) \times 10^{-3} \text{ eV}^2$$

Inverted Hierarchy

$$\sin^2 \theta_{23} = 0.511 \pm 0.055$$

$$\Delta m_{13}^2 = (2.48 \pm 0.10) \times 10^{-3} \text{ eV}^2$$

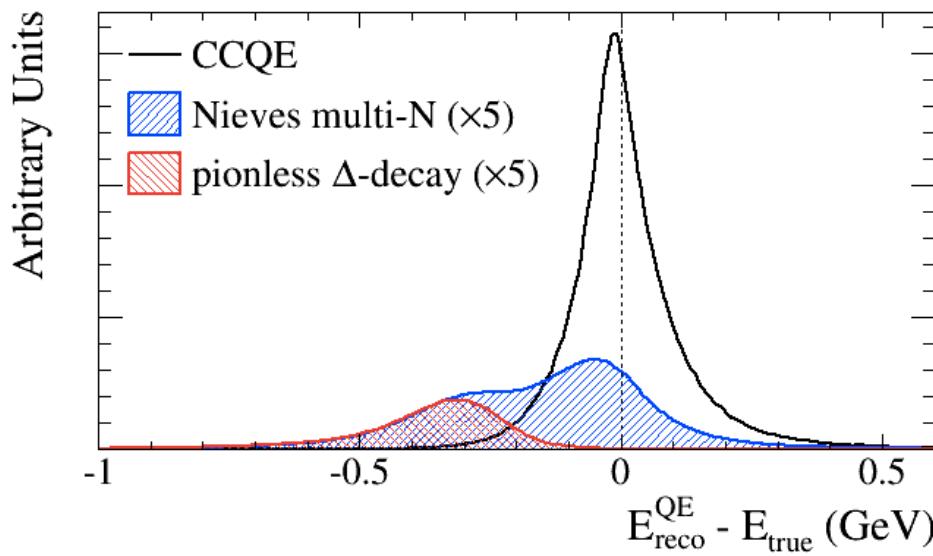
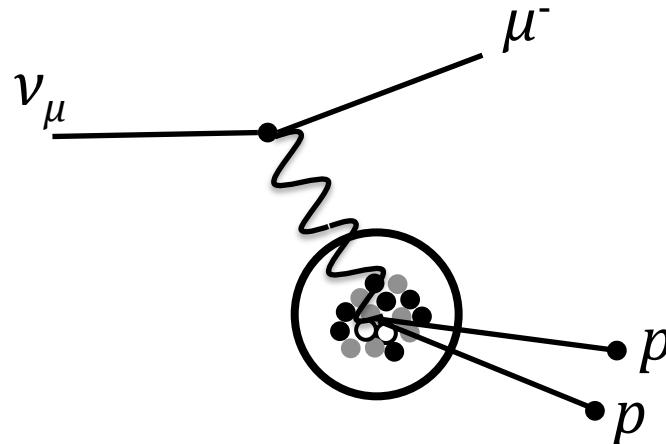
Fit for ν_μ Disappearance



Best fit at maximal disappearance

- Result narrower than sensitivity by 0.04 in $\sin^2(\theta_{23})$

M multinucleon Interactions



- Neutrinos may interact with multiple nucleons
 - Looks CCQE, but has different kinematics
 - Potential explanation for $M_A \approx 1.2 \text{ GeV}$ instead of 1.0 GeV
- Studied potential for bias in our result from neglecting multinucleon interactions
 - Use many fake experiments with random systematic errors

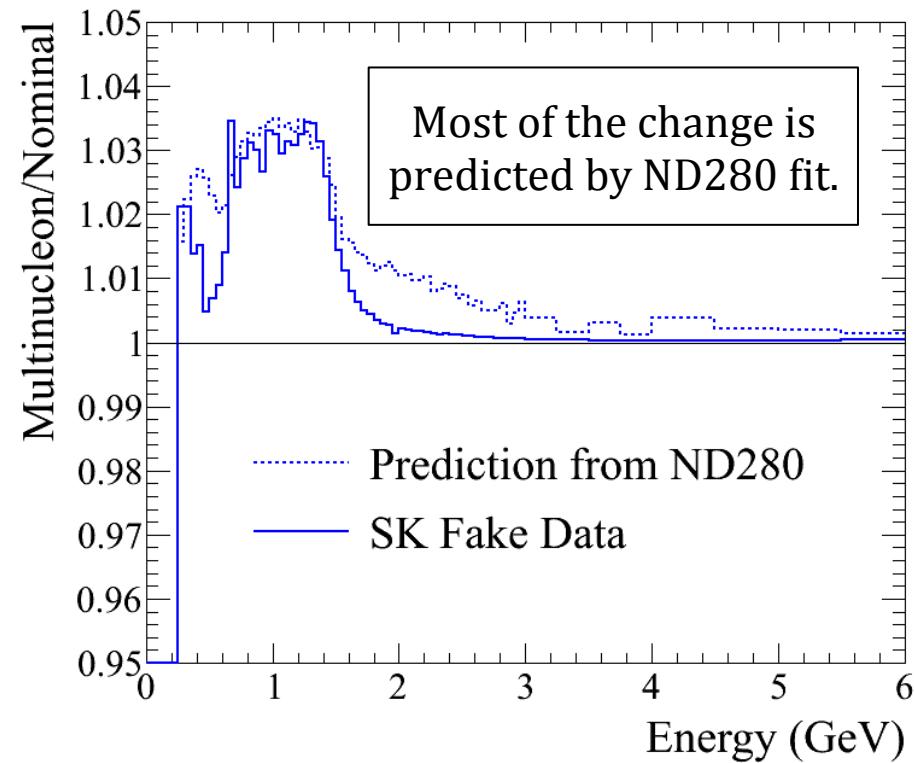
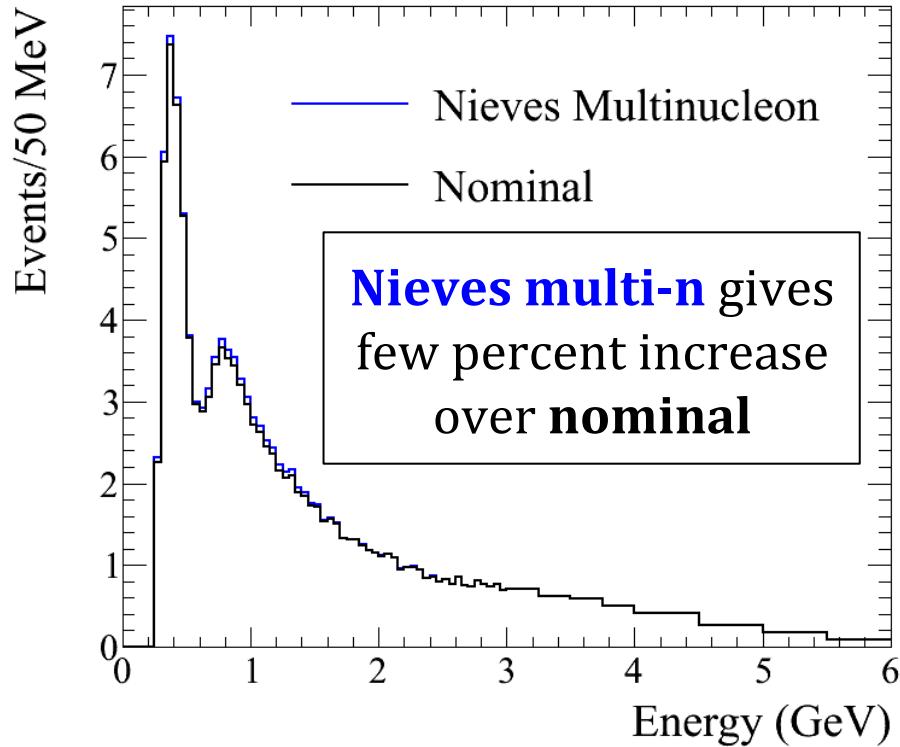
Our model:

J. Nieves et. al., PRC83, 045501 (2011)
J. Sobczyk, PRC86, 015504 (2012)

Suggested potential for bias in oscillations:

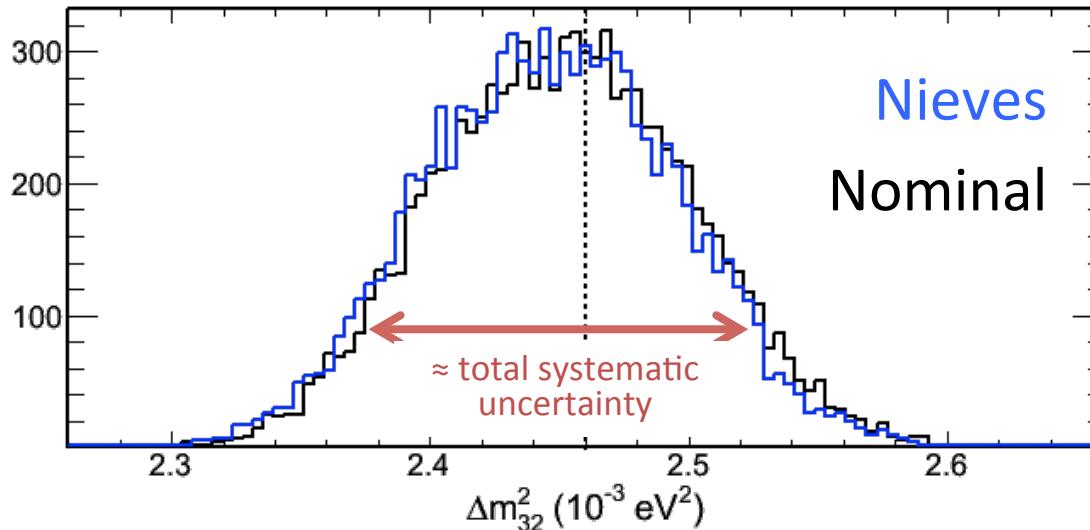
O. Lalakulich and U. Mosel, PRC86, 054606 (2012).
D. Meloni and M. Martini, PLB716, 186 (2012).
P. Coloma, et al, arXiv:1311.4506 (2013).

Effect on SK Spectrum

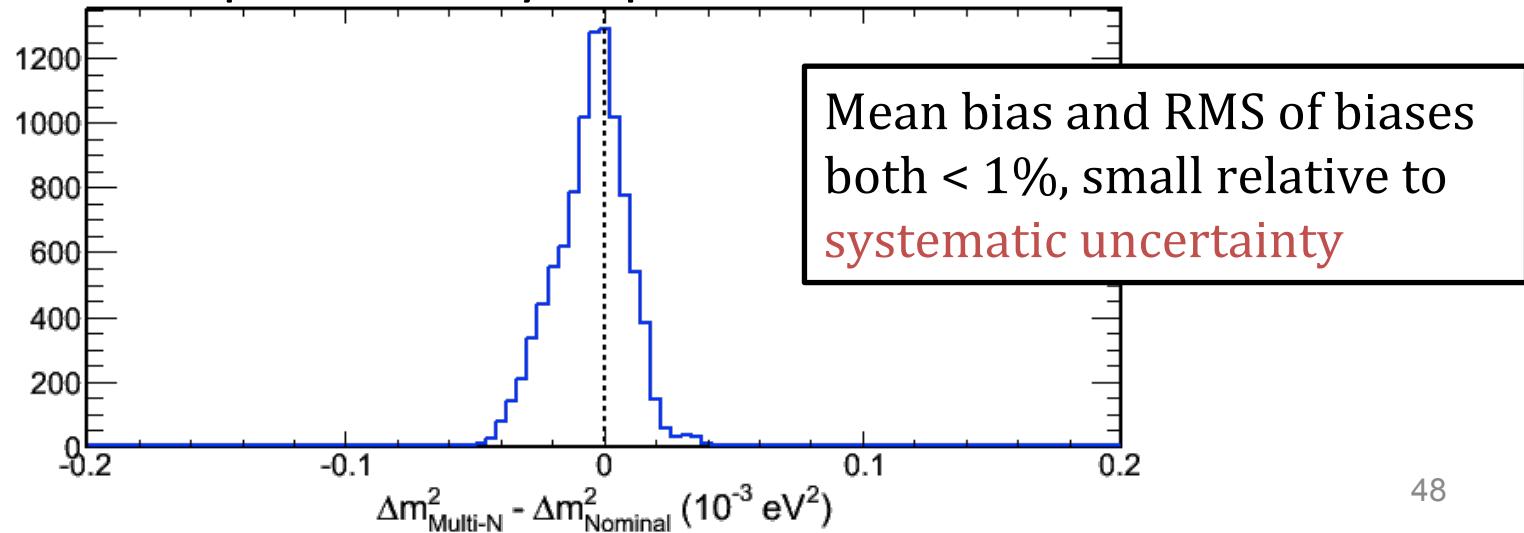


Bias in Δm^2

Distribution of Fake Experiments

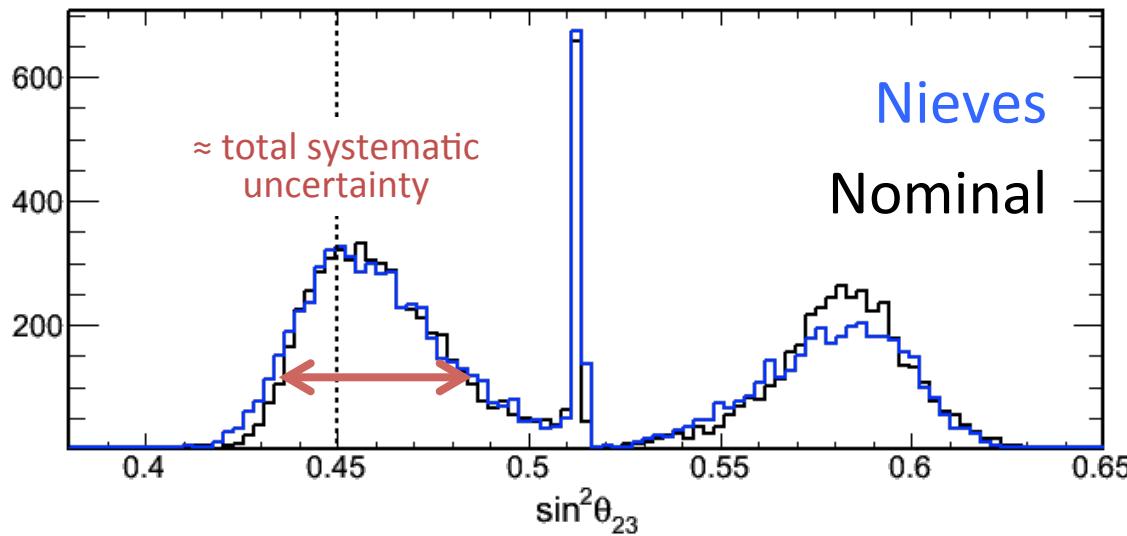


Experiment-by-Experiment Biases

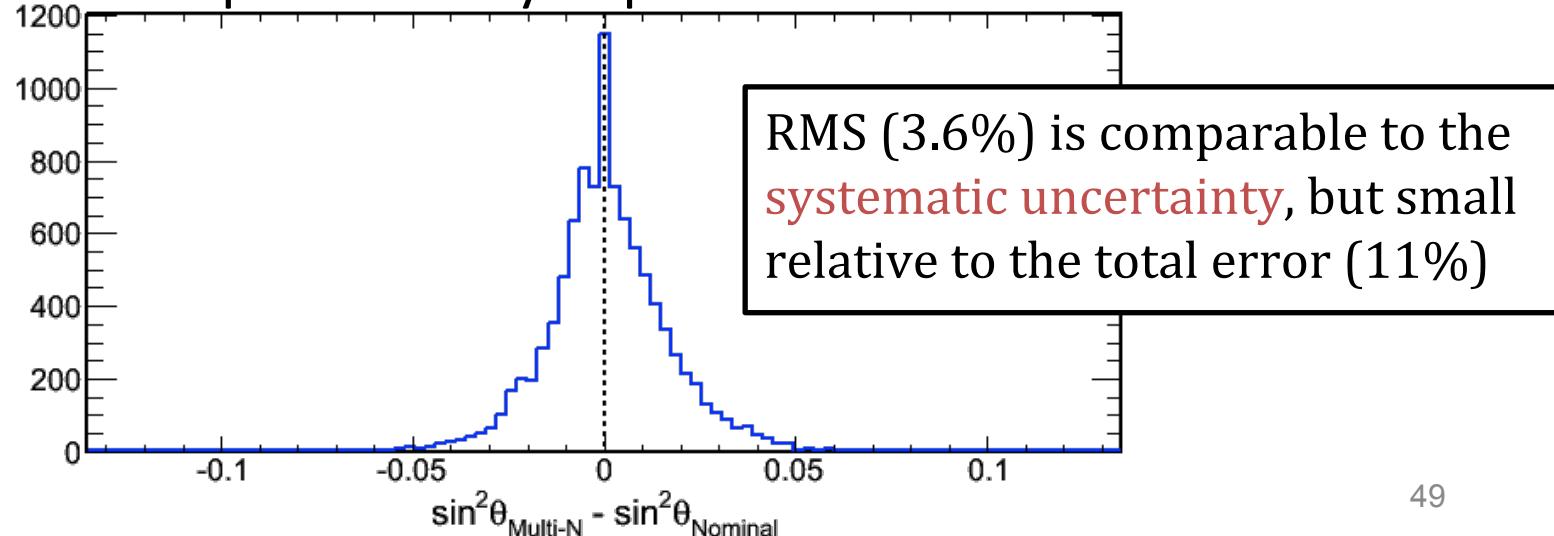


Bias in $\sin^2(\theta_{23})$

Distribution of Fake Experiments

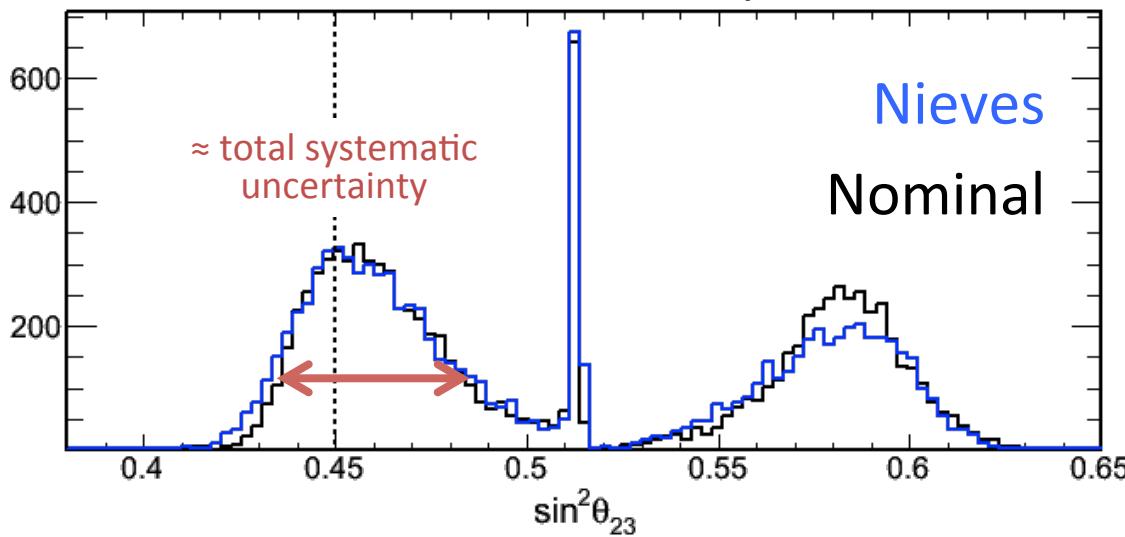


Experiment-by-Experiment Biases



Bias in $\sin^2(\theta_{23})$

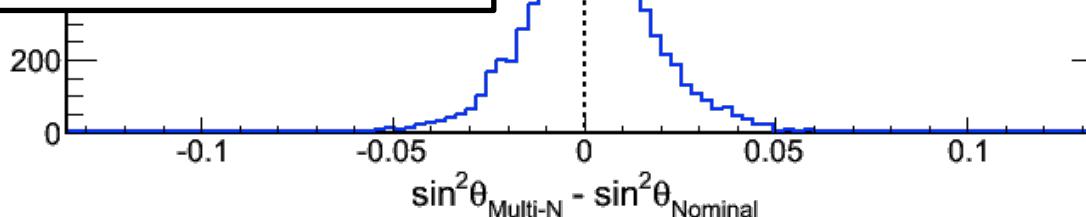
Distribution of Fake Experiments



Experiment-by-Experiment Biases

Not included as a systematic in this analysis, but will be included in future analyses.

RMS (3.6%) is comparable to the systematic uncertainty, but small relative to the total error (11%)



Fit for ν_e Appearance

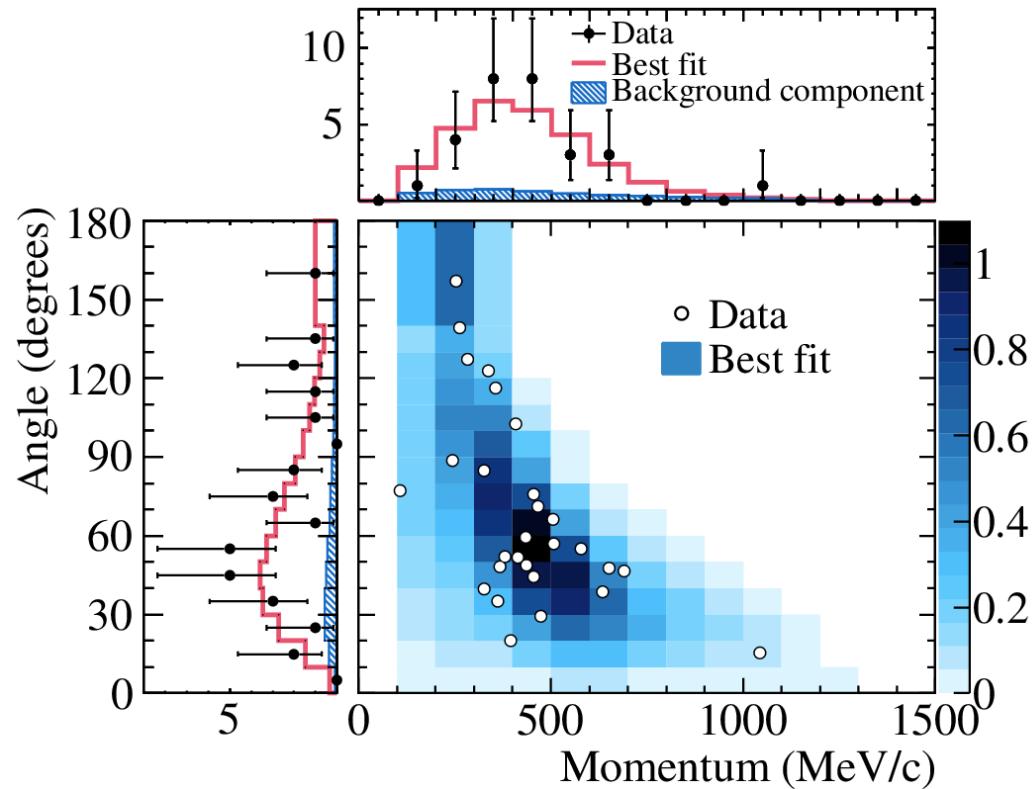
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E_\nu} \right) \left(1 + \frac{4\sqrt{2}G_F n_e E}{\Delta m_{31}^2} (1 - 2 \sin^2 \theta_{13}) \right)$$
$$- \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E_\nu} \right) \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$

CP violation Matter Effects - MH

- Approximation shows 2 leading terms
 - First gives sensitivity to θ_{13} , mass hierarchy
 - Second gives sensitivity to CP violation
- For the ν_e -only analysis, we constrained θ_{23} with the 2013 ν_μ analysis

Fit for ν_e Appearance

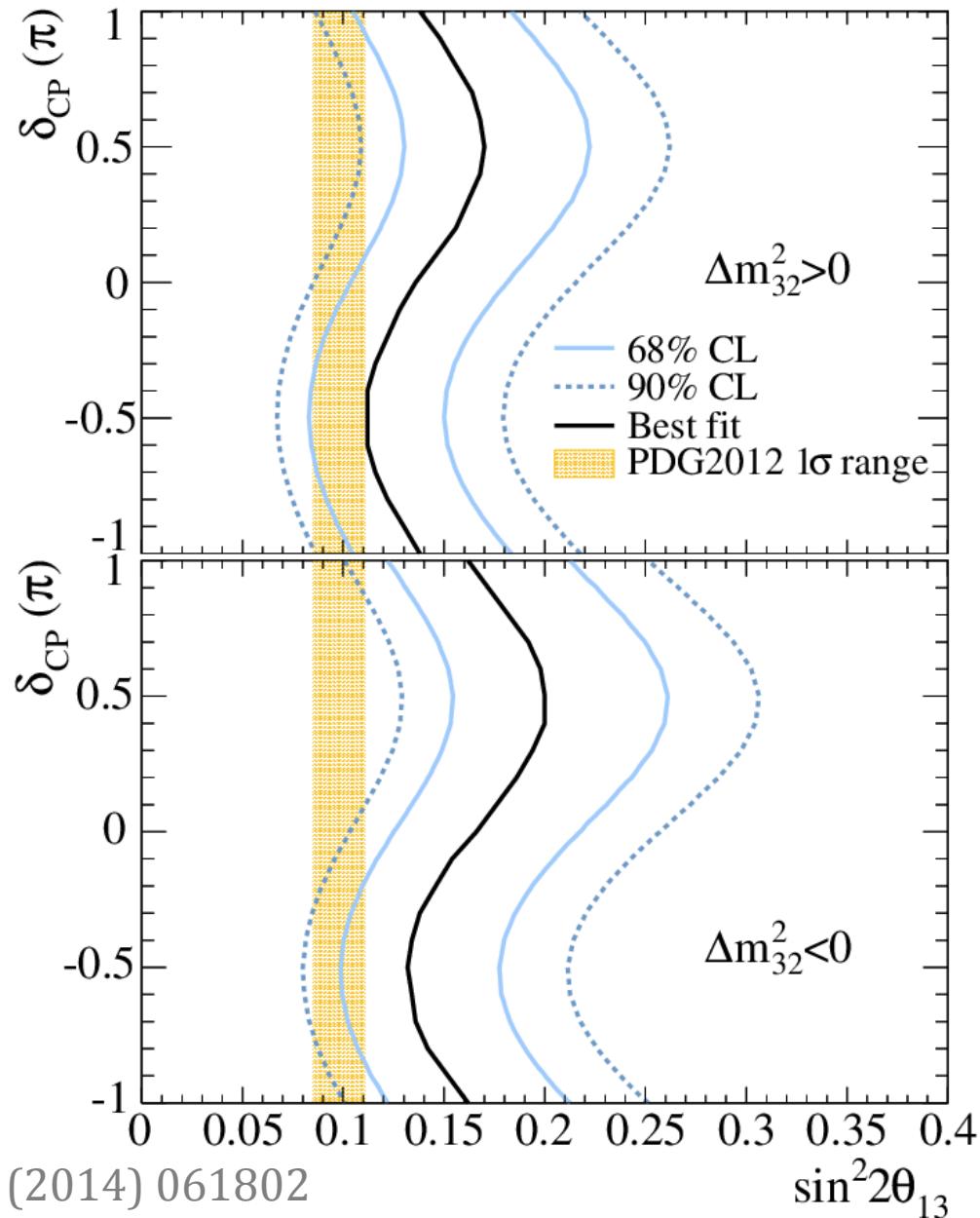
- Fit in e^- momentum and angle
 - Contains same information as E_{rec}
 - Helps separate backgrounds



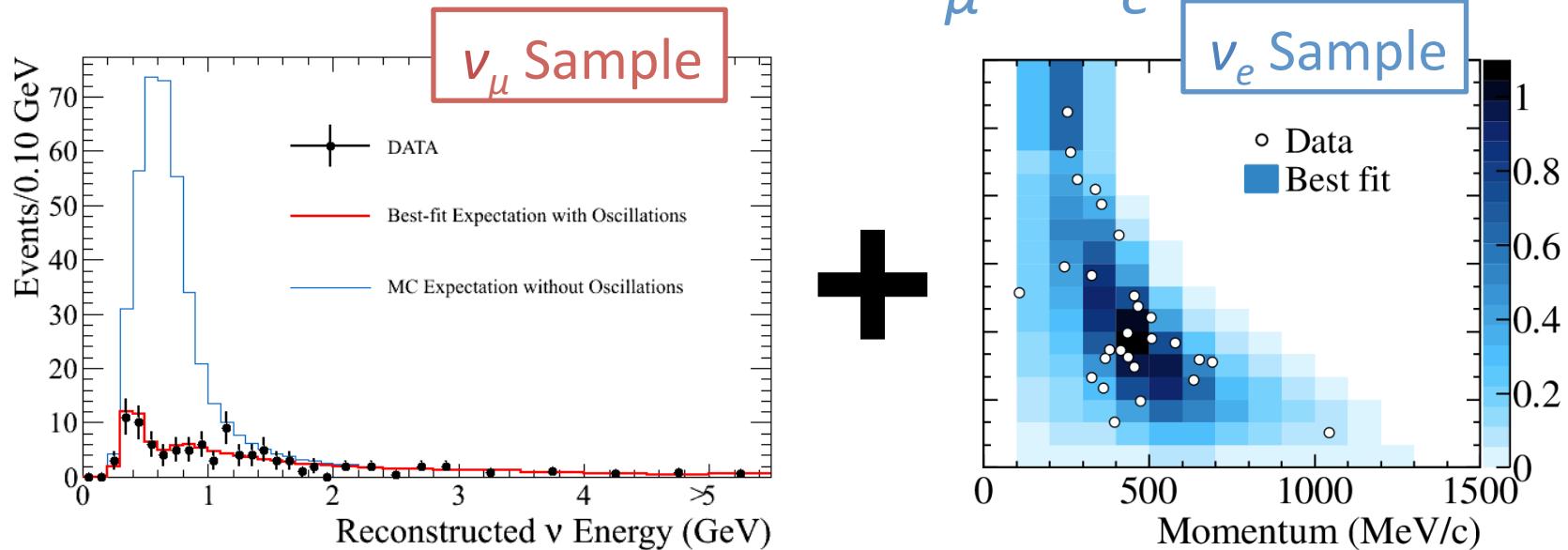
No appearance excluded at $> 7\sigma$!

Fit for ν_e Appearance

- Some mild tension between the large appearance signal and reactor measurements
- Hints towards $\delta_{cp} \approx -\pi/2$

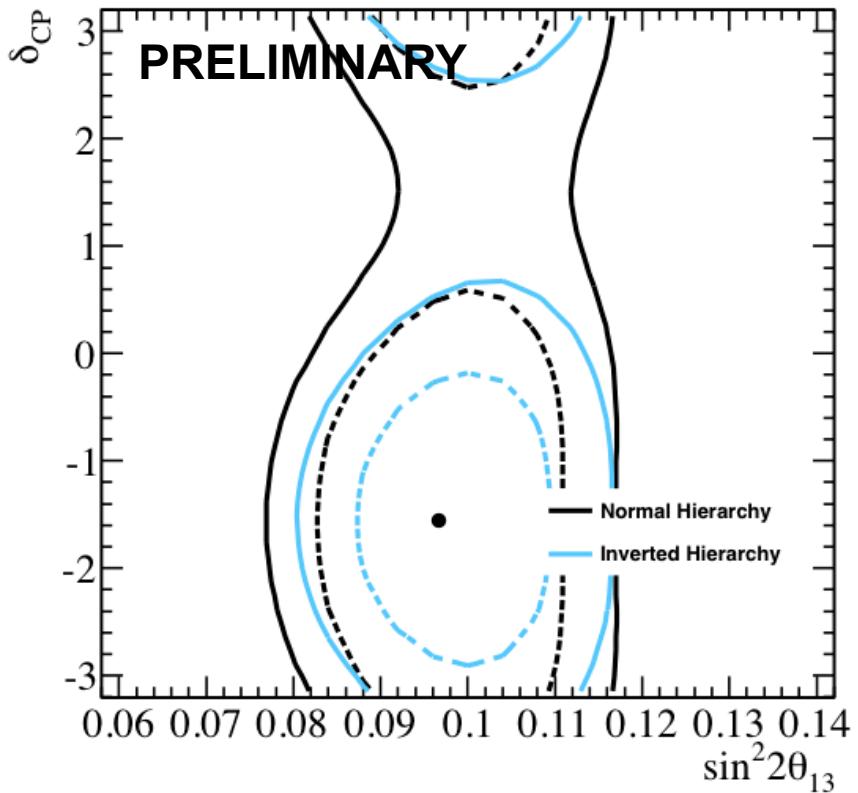


Joint Fits to $\nu_\mu + \nu_e$

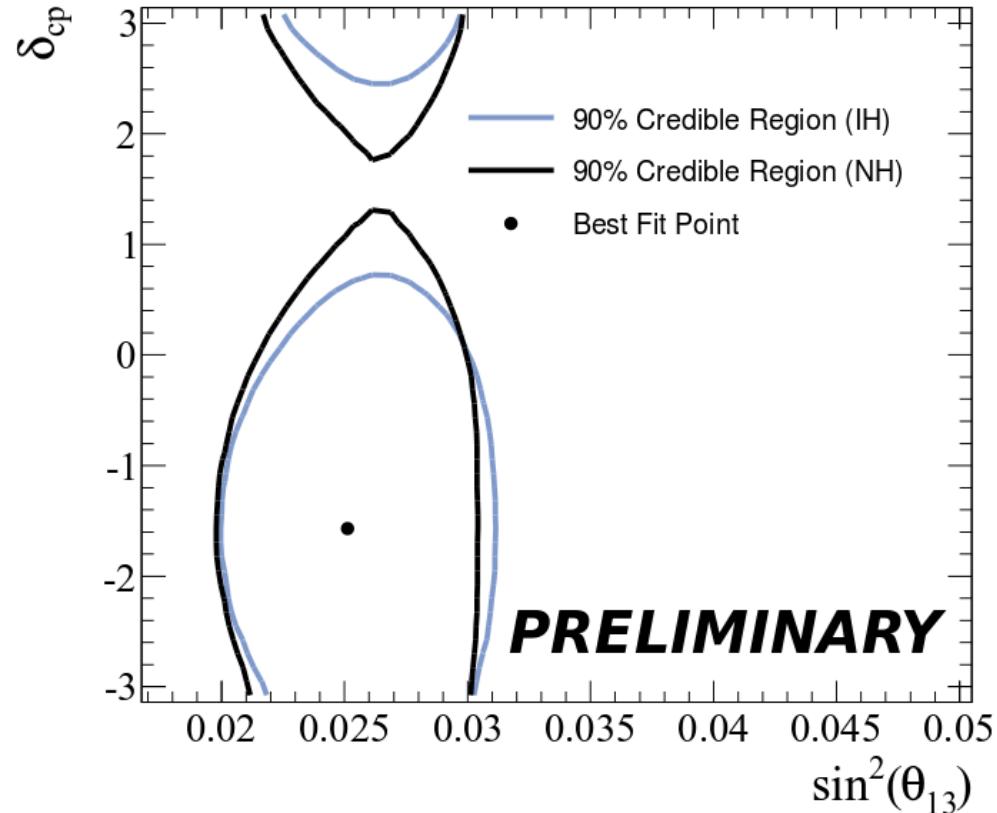


- Likelihood ratio fit of ν_μ and ν_e samples
- Both Frequentist and Bayesian analyses performed
- Simultaneous fit for: $\delta_{cp}, \theta_{13}, \theta_{23}, \Delta m_{32}^2$

Frequentist and Bayesian Contours



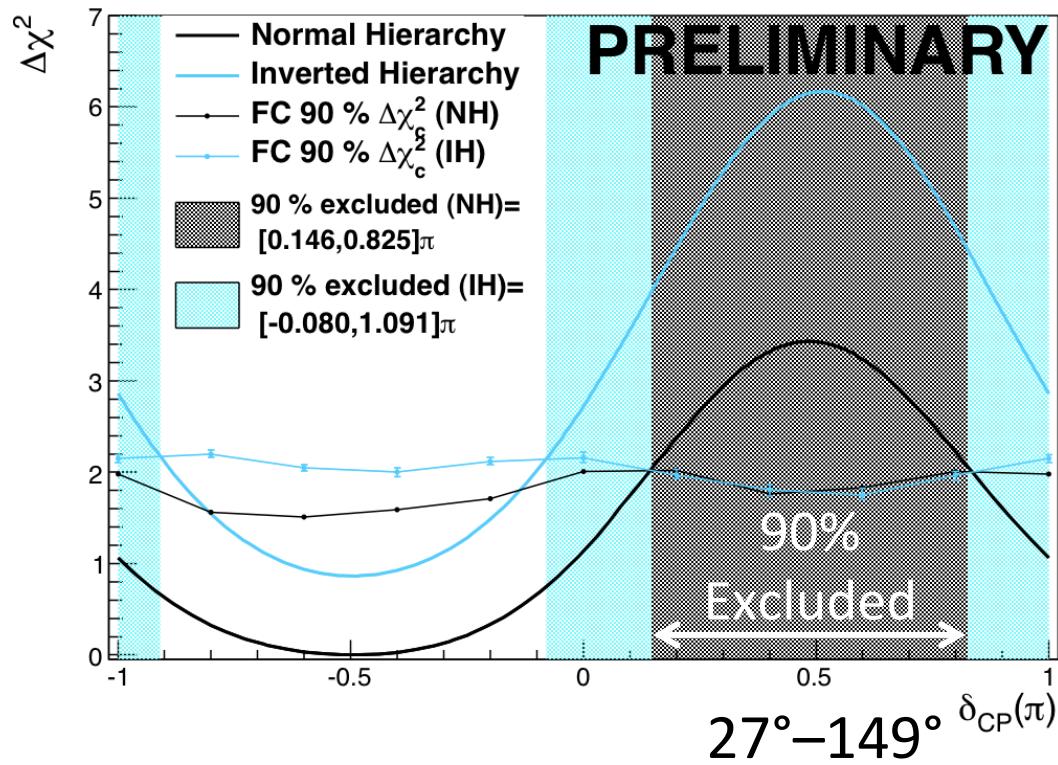
Frequentist confidence intervals



Bayesian credible intervals

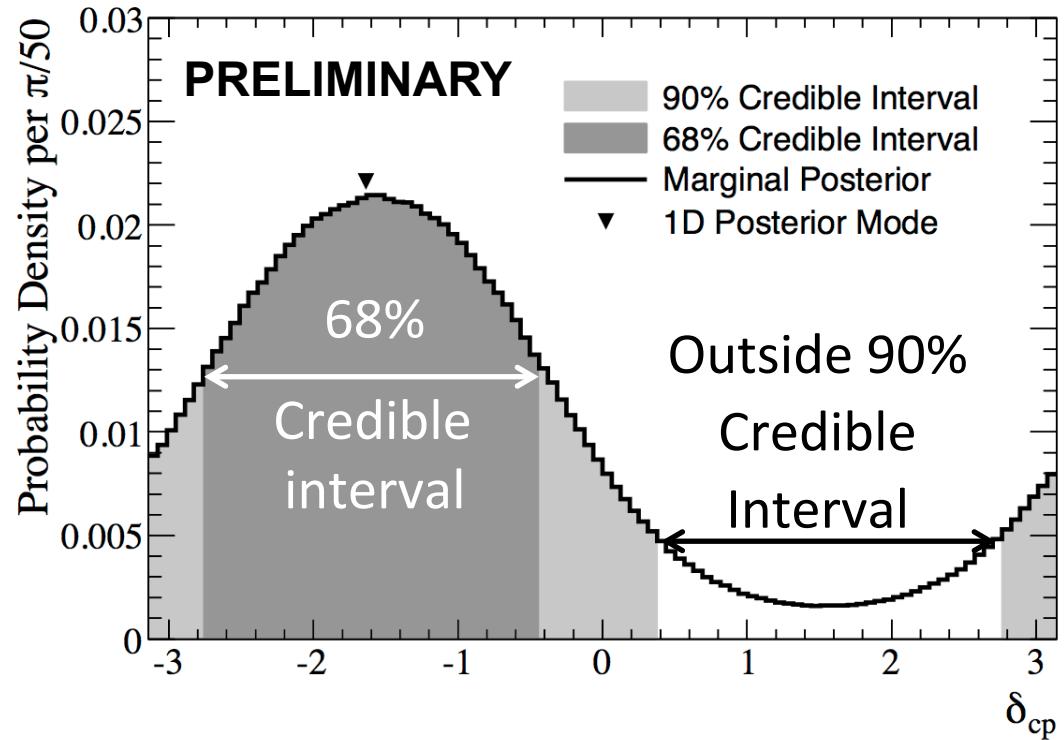
Frequentist δ_{CP} Constraint

- Now, include the reactor constraint on θ_{13} .
 - $\sin^2(2\theta_{13}) = 0.095 \pm 0.010$
 -   
from the PDG, PRD86 010001
(2012, 2013 update)
- Feldman-Cousins used to determine confidence intervals for NH and IH separately.



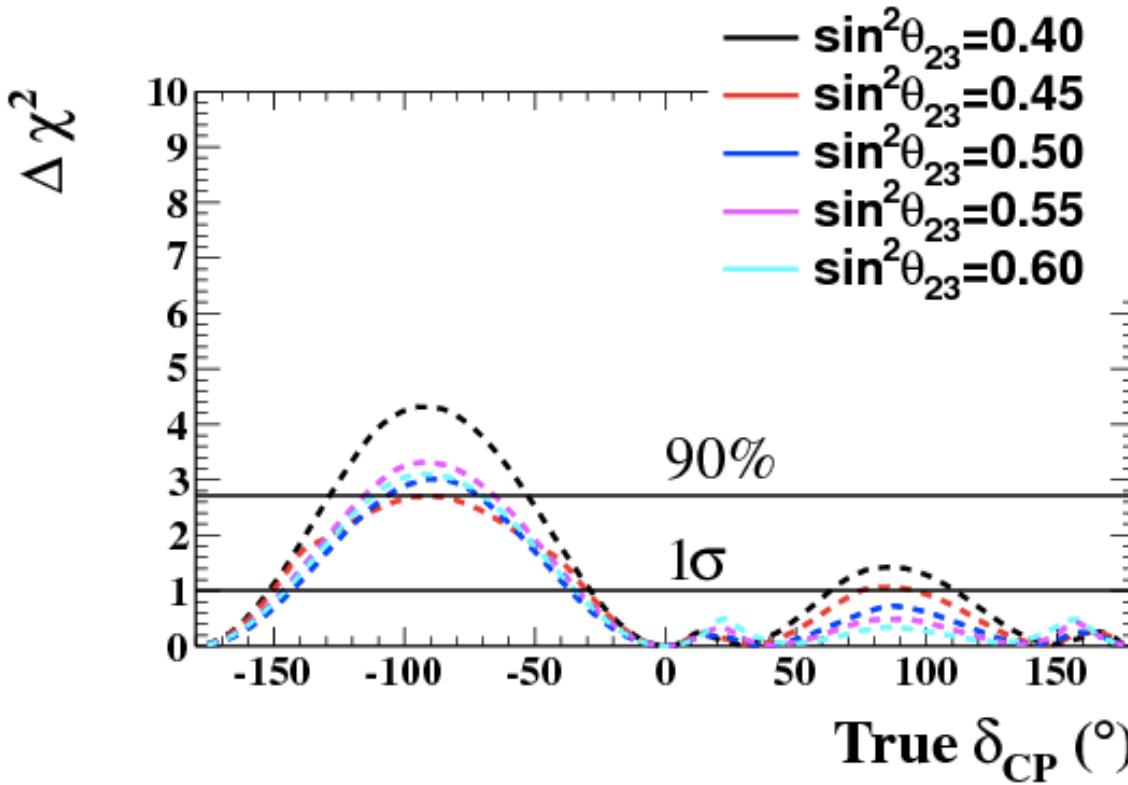
Bayesian δ_{CP} , MH, Octant Constraints

- Bayesian analysis can marginalize over the mass hierarchy
- Compare probabilities of different hierarchies and θ_{23} octants



	NH	IH	Sum
$\sin^2(\theta_{23}) \leq 0.5$	18%	8%	26%
$\sin^2(\theta_{23}) > 0.5$	50%	24%	74%
Sum	68%	32%	

Future Sensitivity

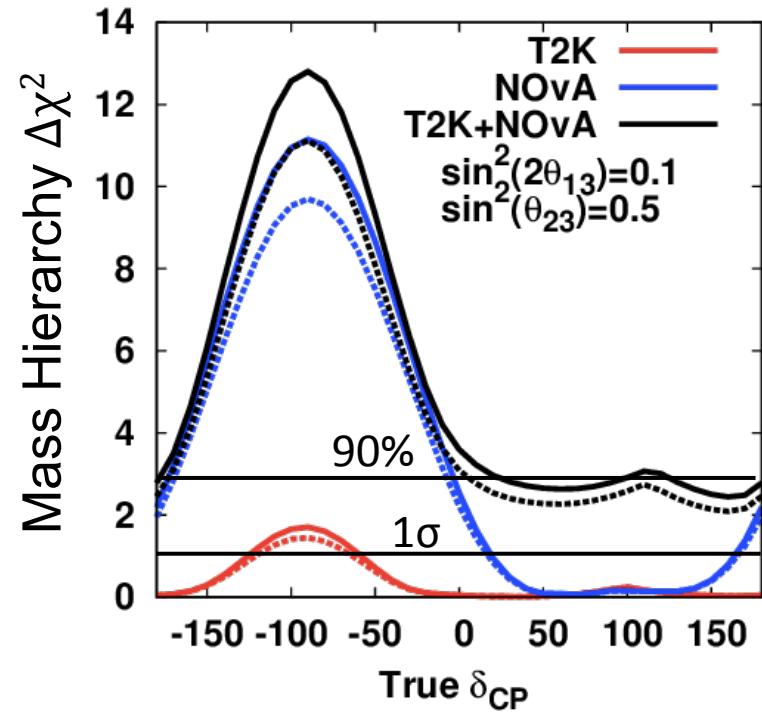
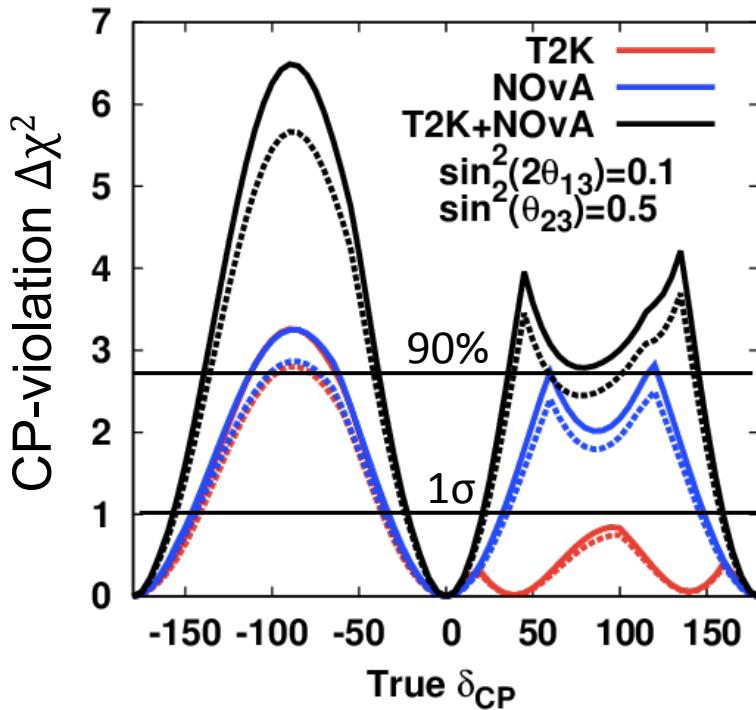


Assumptions

- 7.8×10^{21} POT
- $\sin^2(2\theta_{13}) = 0.1$ with ultimate reactor precision
- $\Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$
- $\sin^2(\theta_{23})$ as shown
- Normal Hierarchy
- Conservative (2012) systematic errors, correlated between nu and antinu

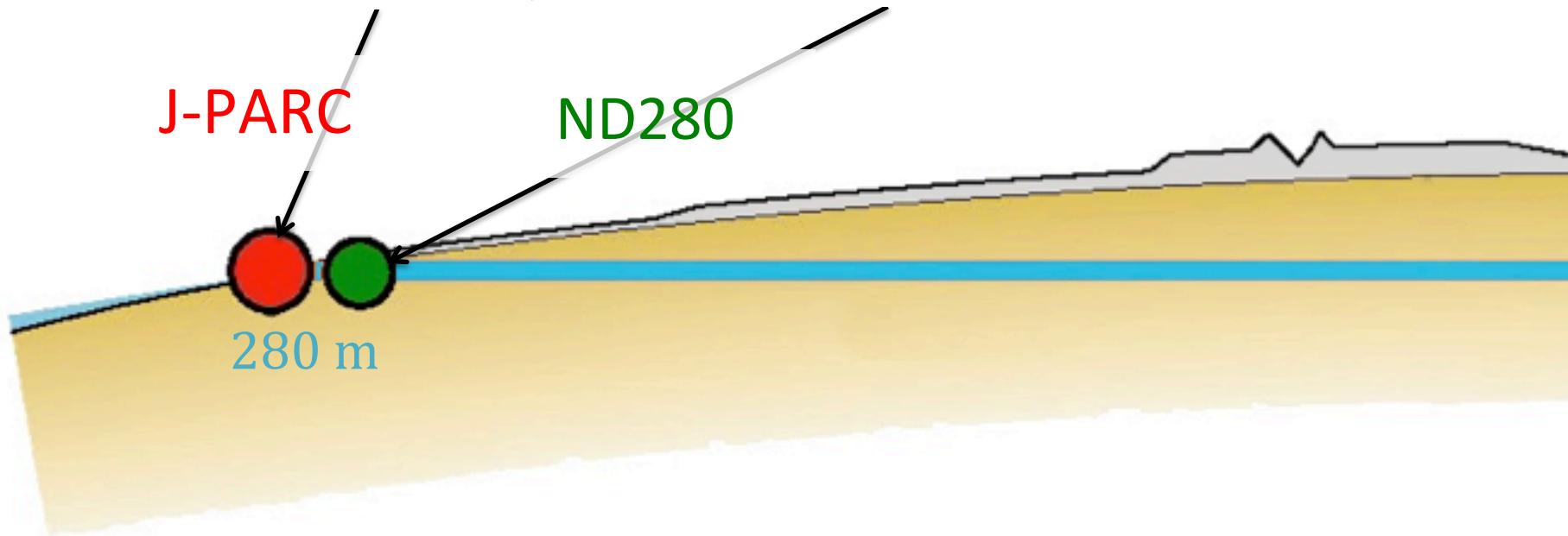
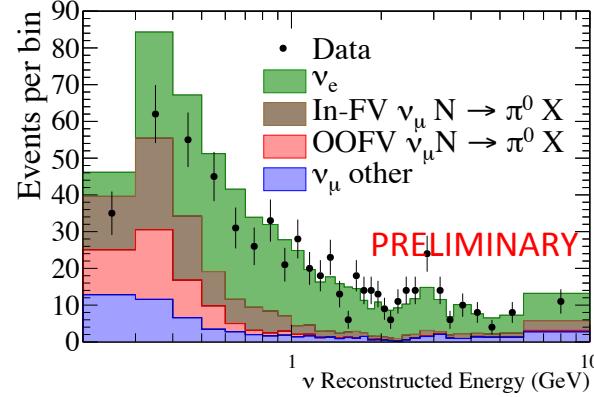
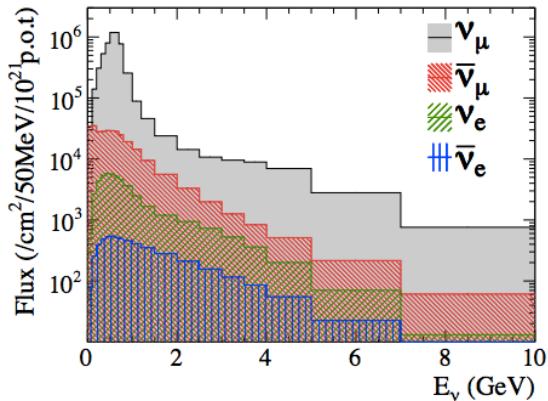
- Evaluated potential future sensitivity under different running conditions
 - 50% neutrino/50% antineutrino seems to be the optimal mix under most circumstances

Future Sensitivity with NOvA

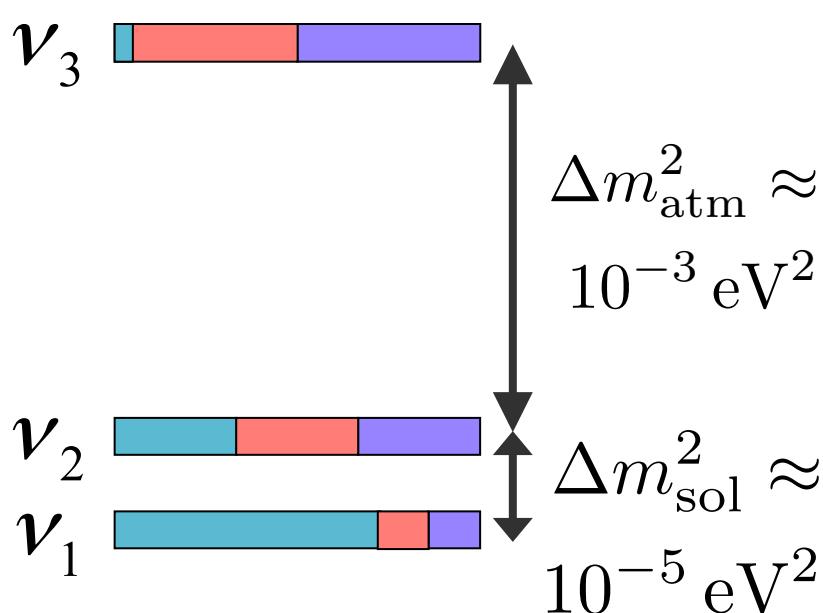


- A joint analysis with NOvA:
 - Increases significance of the “luckiest” point
 - Adds sensitivity in δ_{CP} regions where there would be none.
- Same assumptions, plus
 - Choose $\sin^2(\theta_{23}) = 0.5$
 - 3.6×10^{21} NOvA POT, even split
 - Shown both without (solid) and with (dashed) systematic errors

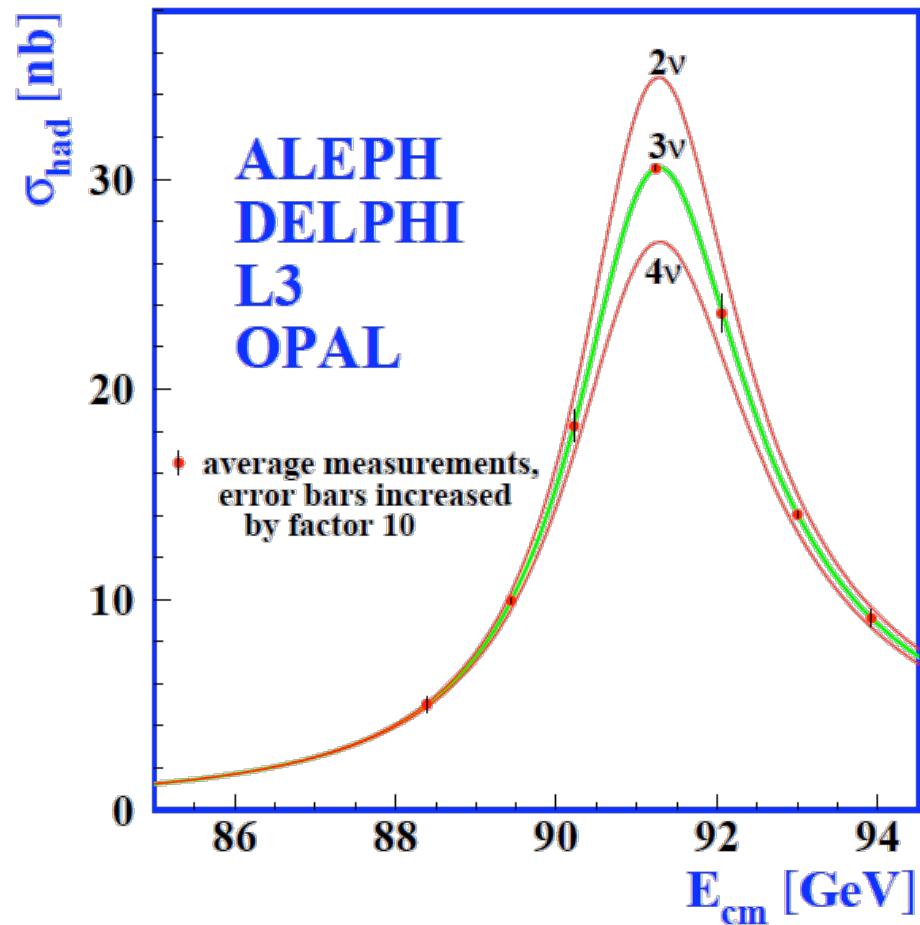
Short-baseline Analysis



Three Neutrinos



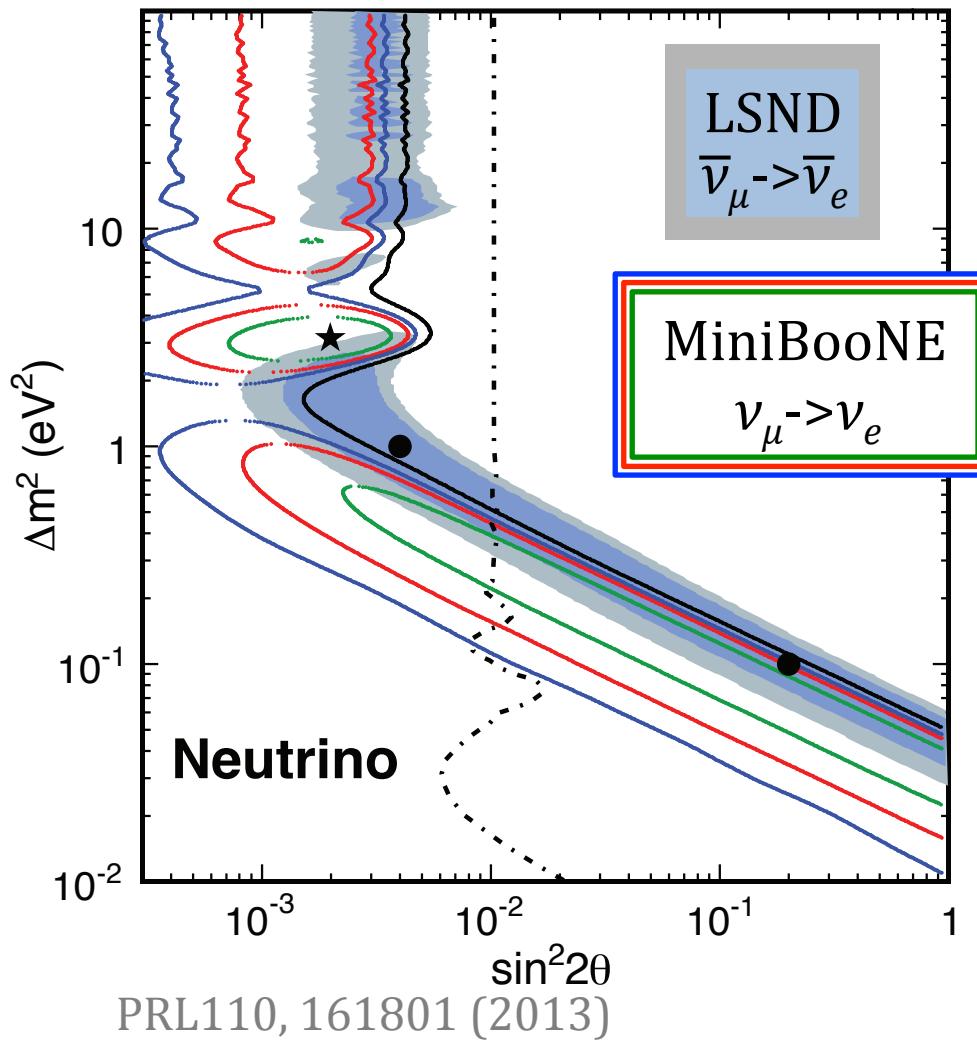
2 mass splittings
imply mixing among
3 neutrino flavors



Measurements at LEP tell us that the Z^0 couples to only 3 light neutrinos

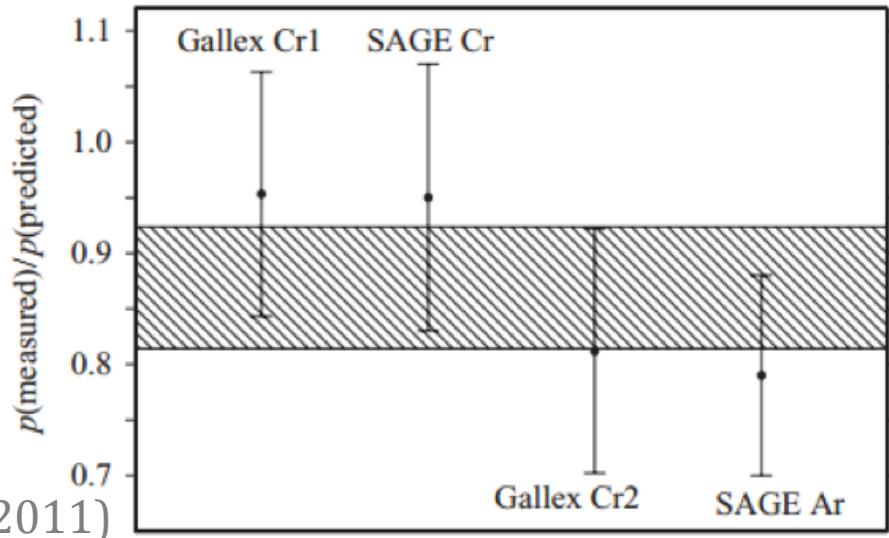
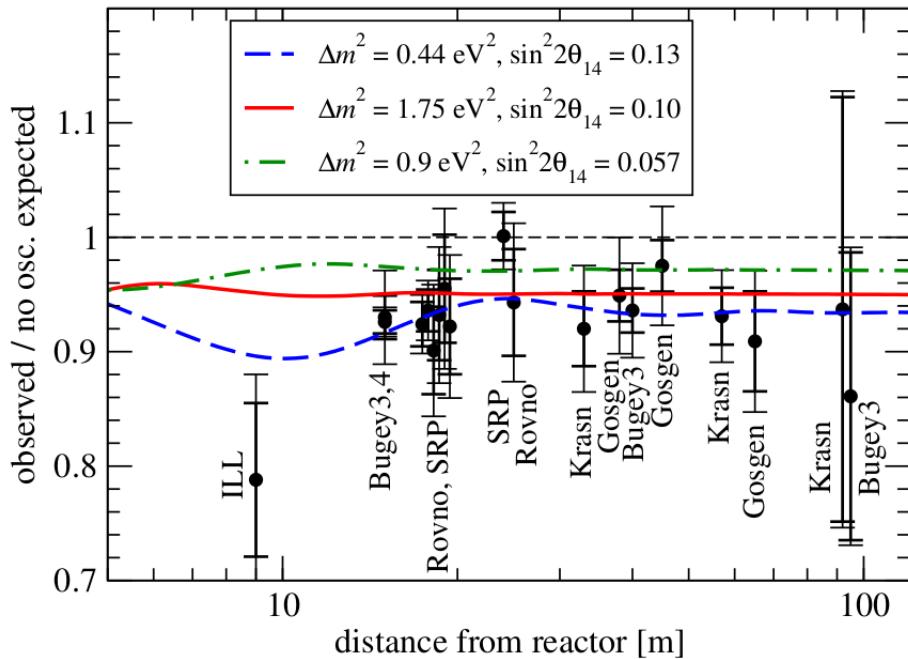
ν_e Appearance at 1 m/MeV?

- LSND
 - Anti- ν_e appearance in a stopped- π beam
 - $L \sim 30$ m, $E \sim 30$ MeV $\rightarrow \Delta m^2 \sim 1$ eV 2
- MiniBooNE
 - ν_e and anti- ν_e appearance, different beam
 - $L \sim 500$ m, $E \sim 500$ MeV
- Not consistent with other oscillation measurements

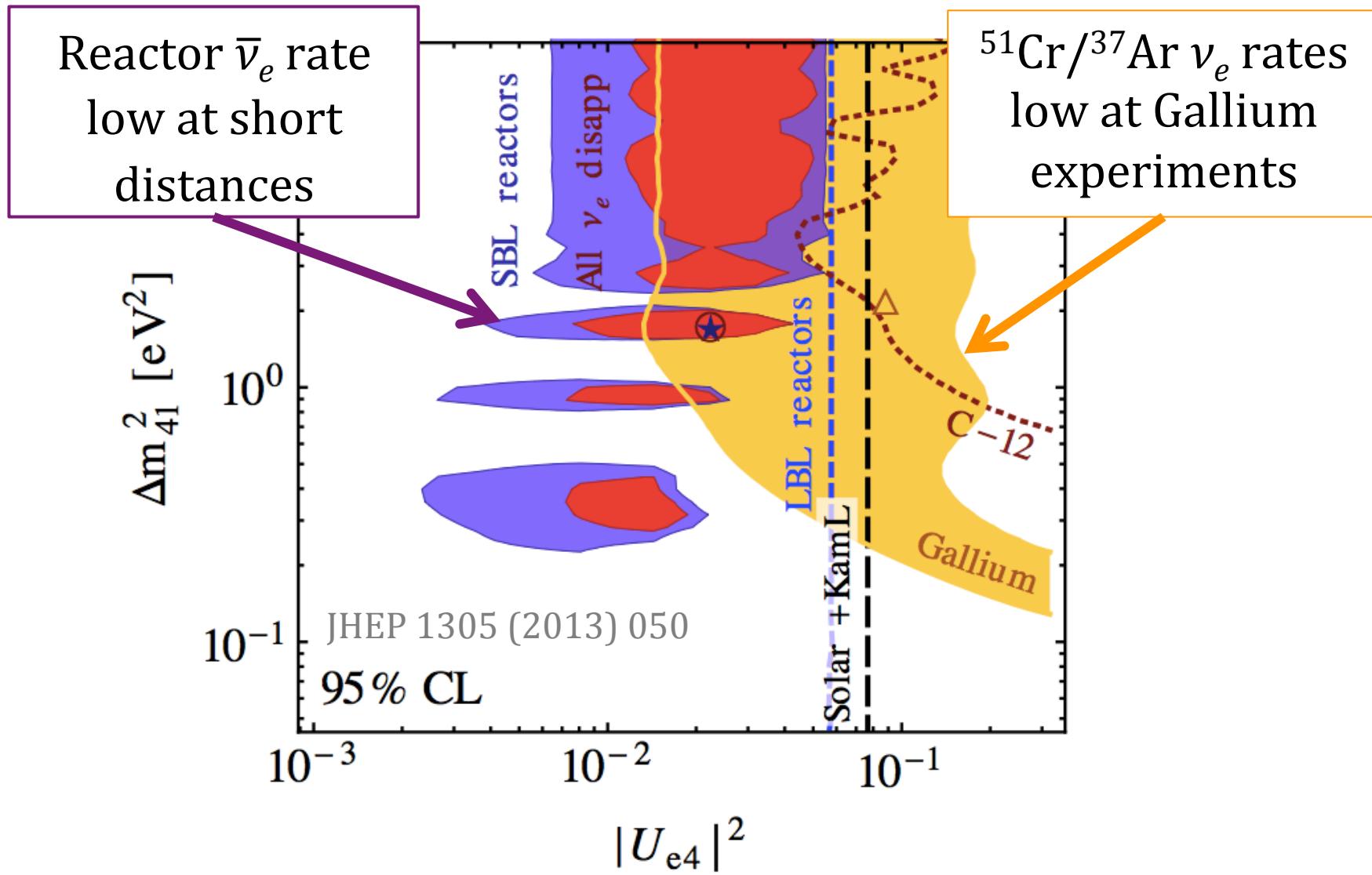


ν_e Disappearance at 1 m/MeV?

- With 2010 flux calculation, most short-baseline reactor experiments have deficits
 - $R_{avg} = 0.927 \pm 0.023$
 - $L \sim 10\text{-}100 \text{ m}, E \sim 5 \text{ MeV}$
- Lower rate than expected from radioactive calibration sources at gallium solar experiments.
 - $R_{avg} = 0.87 \pm 0.05$



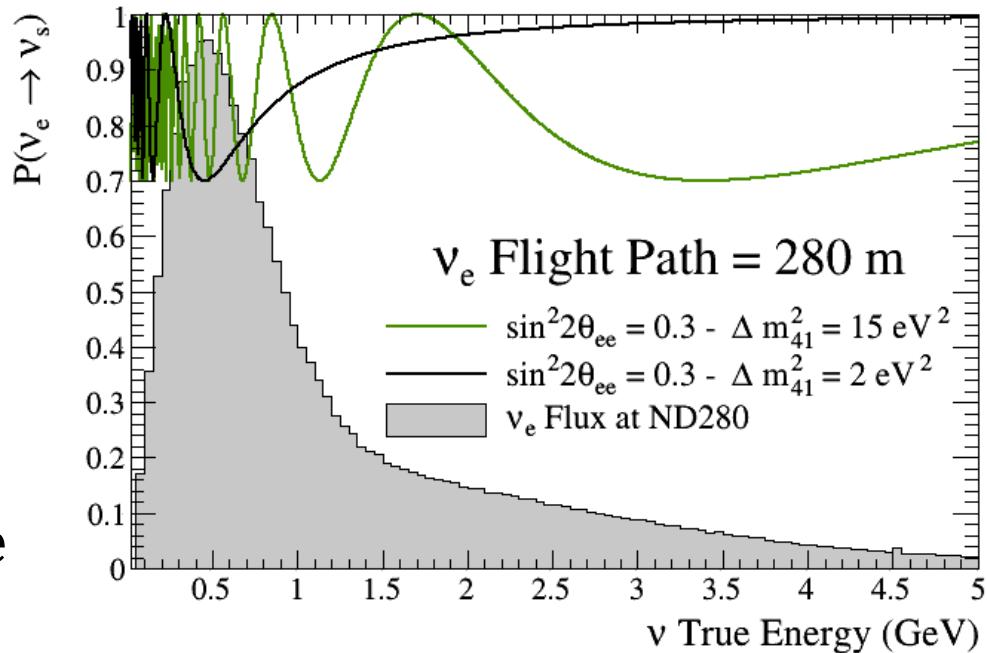
ν_e Disappearance at 1 m/MeV?

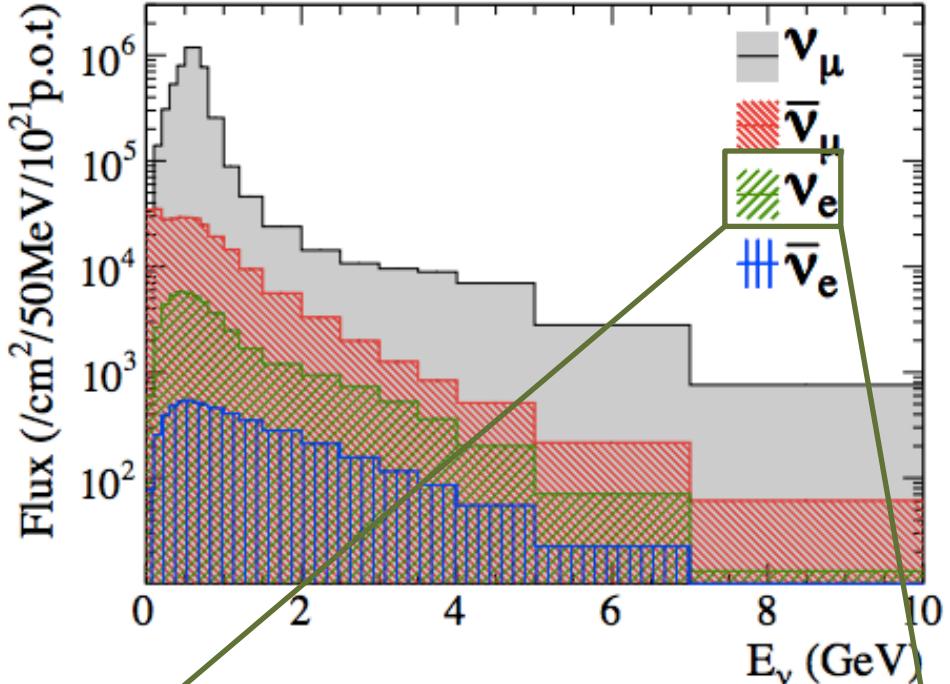


Sterile Nus at ND280

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{ee}) \sin^2 \left(1.27 \Delta m_{41}^2 \frac{L \text{ [m]}}{E \text{ [MeV]}} \right)$$

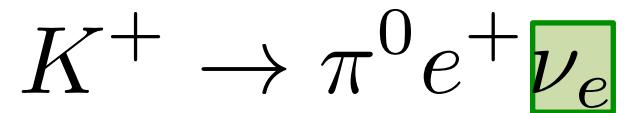
- Look for ν_e disappearance in the T2K beam
- Search for a sterile neutrino signature in the 3+1 framework
- Sensitive above $\sim 2 \text{ eV}^2$
- Assume no ν_μ disappearance and no ν_e appearance
 - Equivalent to $|U_{\mu 4}|^2 = 0$





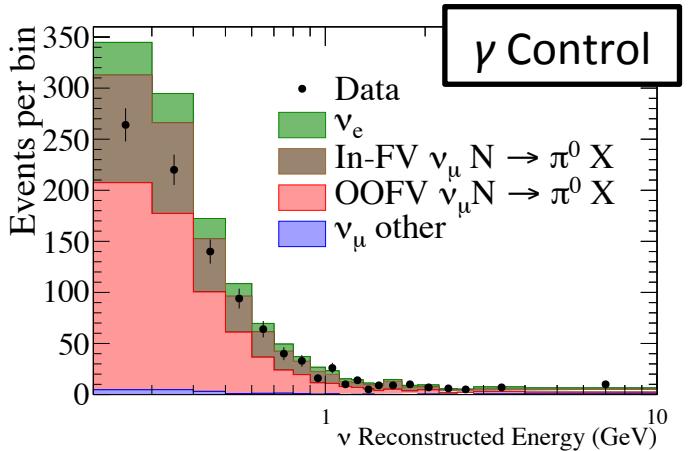
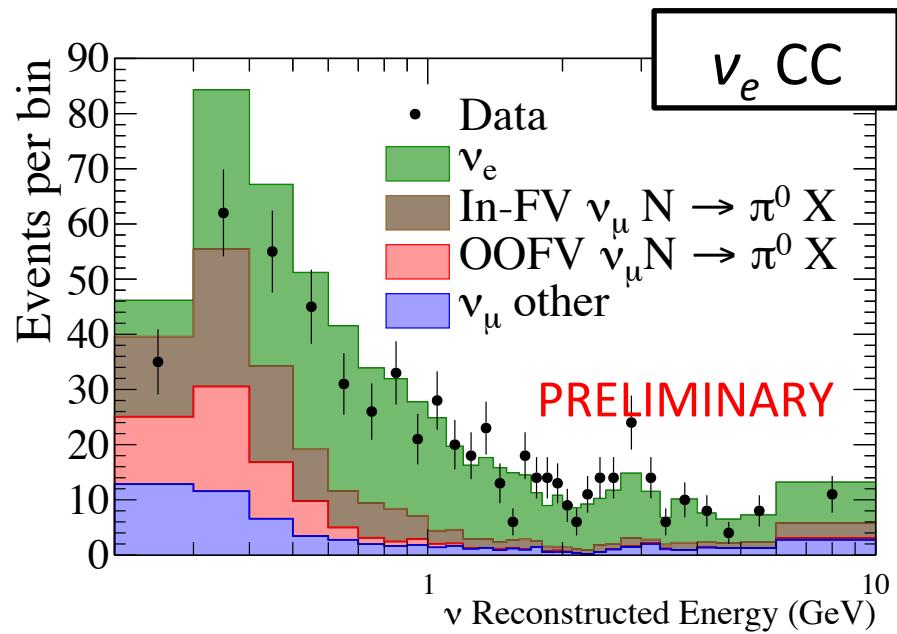
ν_e Flux Component

- The T2K beam has a 1.1% ν_e component
 - Primarily from μ and K decays

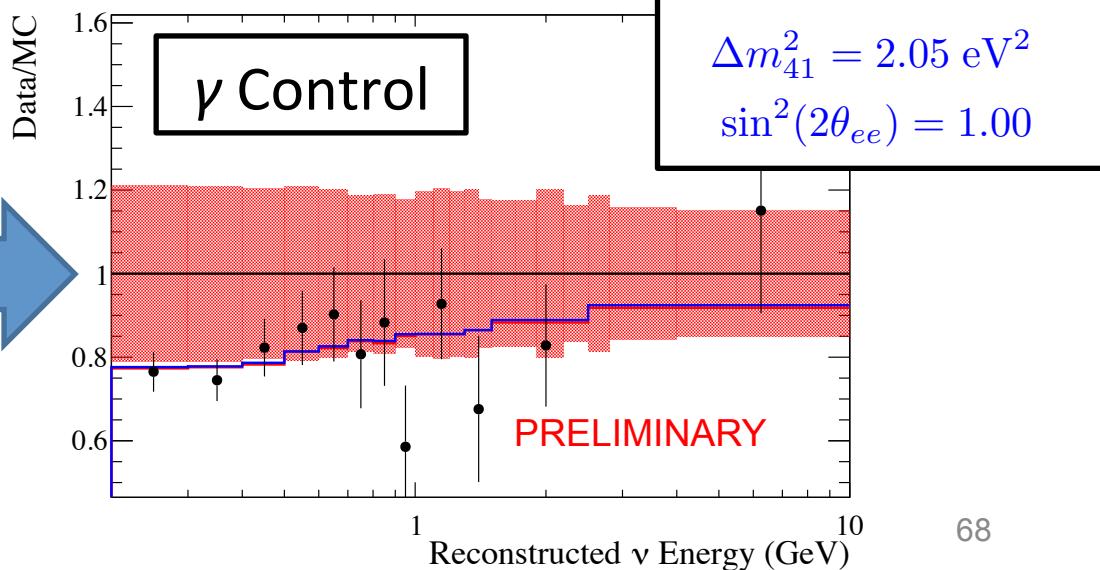
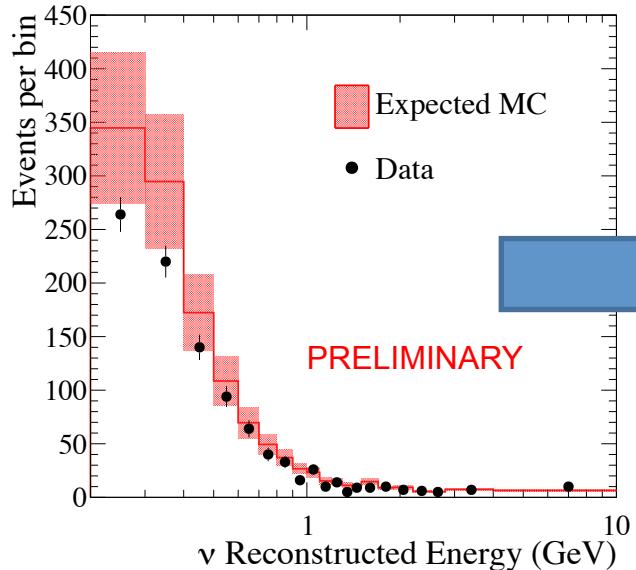
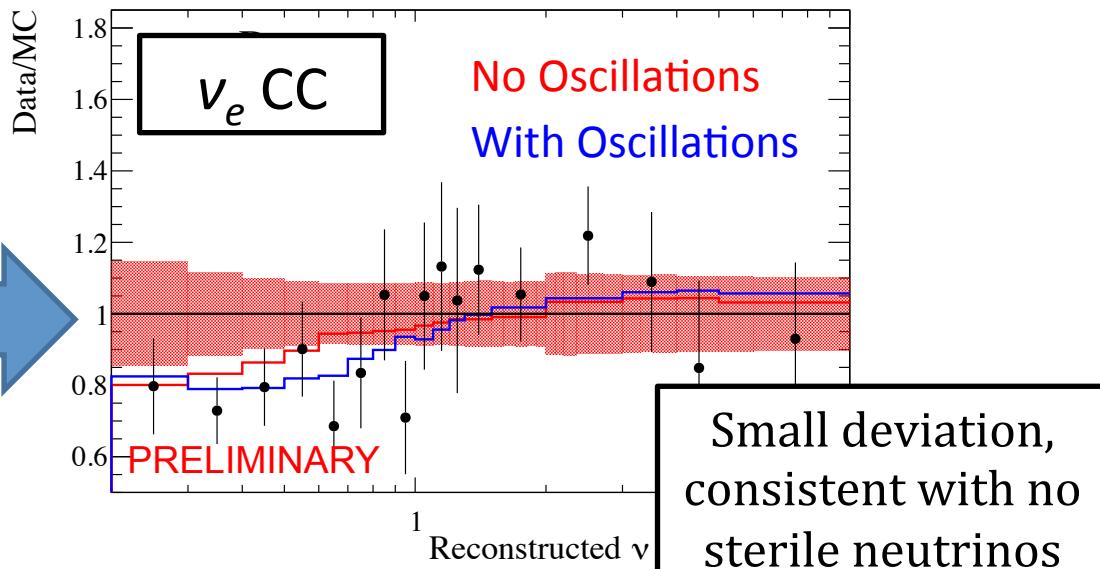
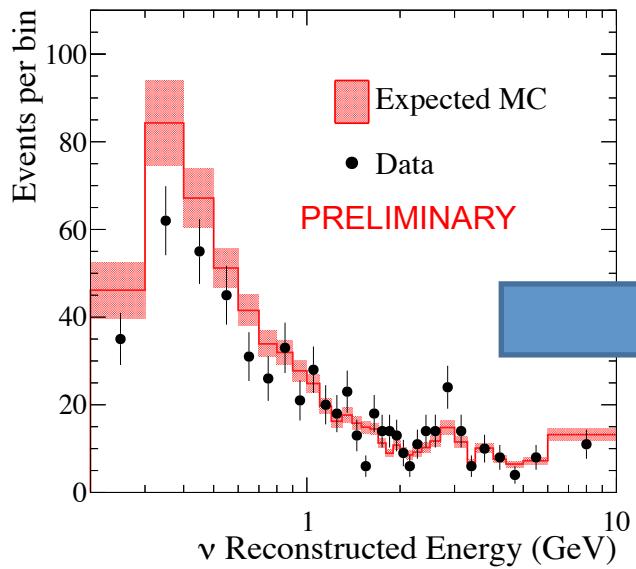


The ν_e Sample

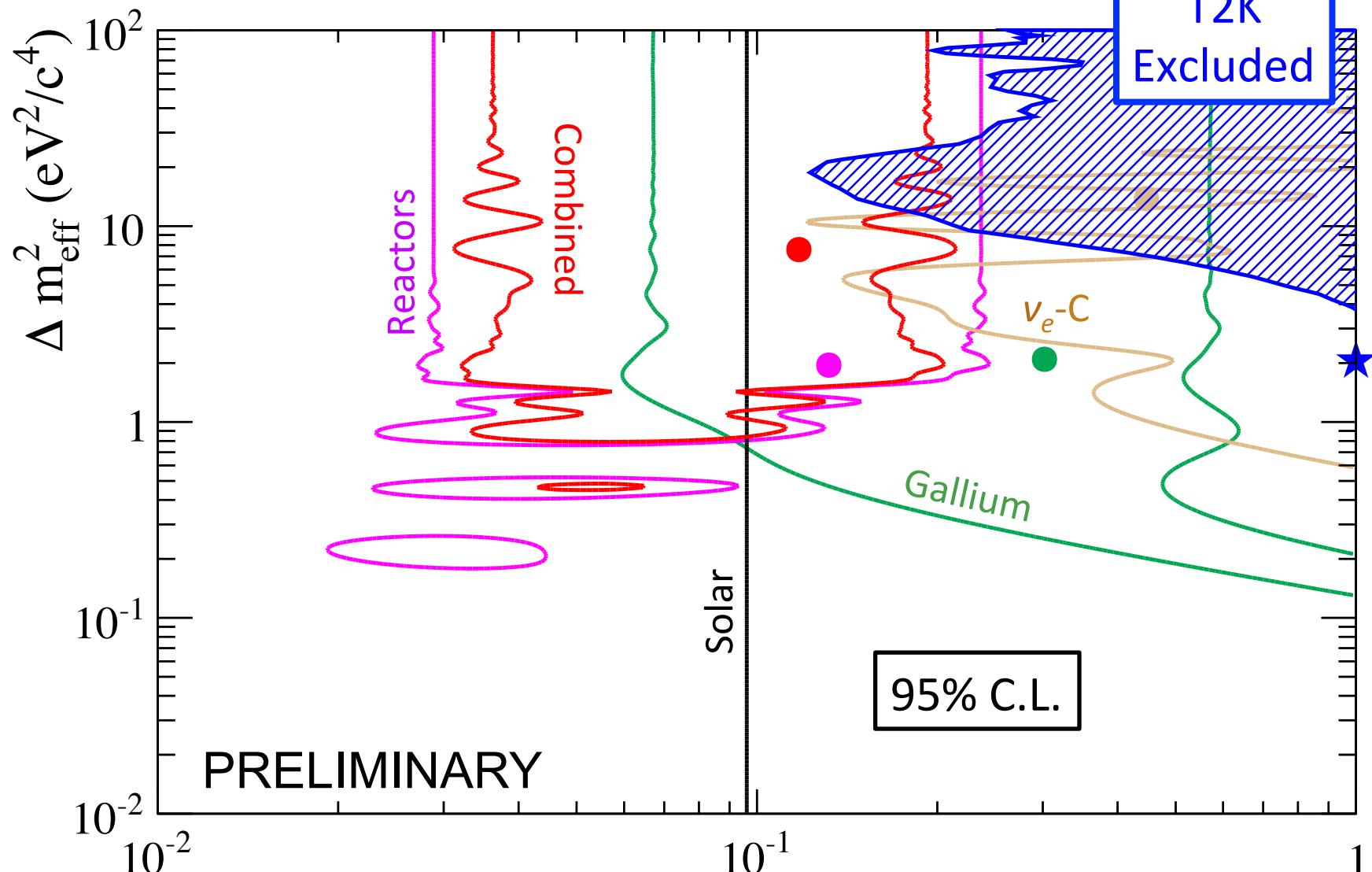
- Select ν_e CC-like events
 - Negative e -like track
 - No upstream activity
- Constraint π^0 background with γ control sample
 - Simultaneous fit to sample of conversion γ 's from π^0 's
- Constrain flux and cross section with ND280 ν_μ sample
 - Assuming no ν_μ disappearance



Sterile ν Fit Results



Sterile ν Contours

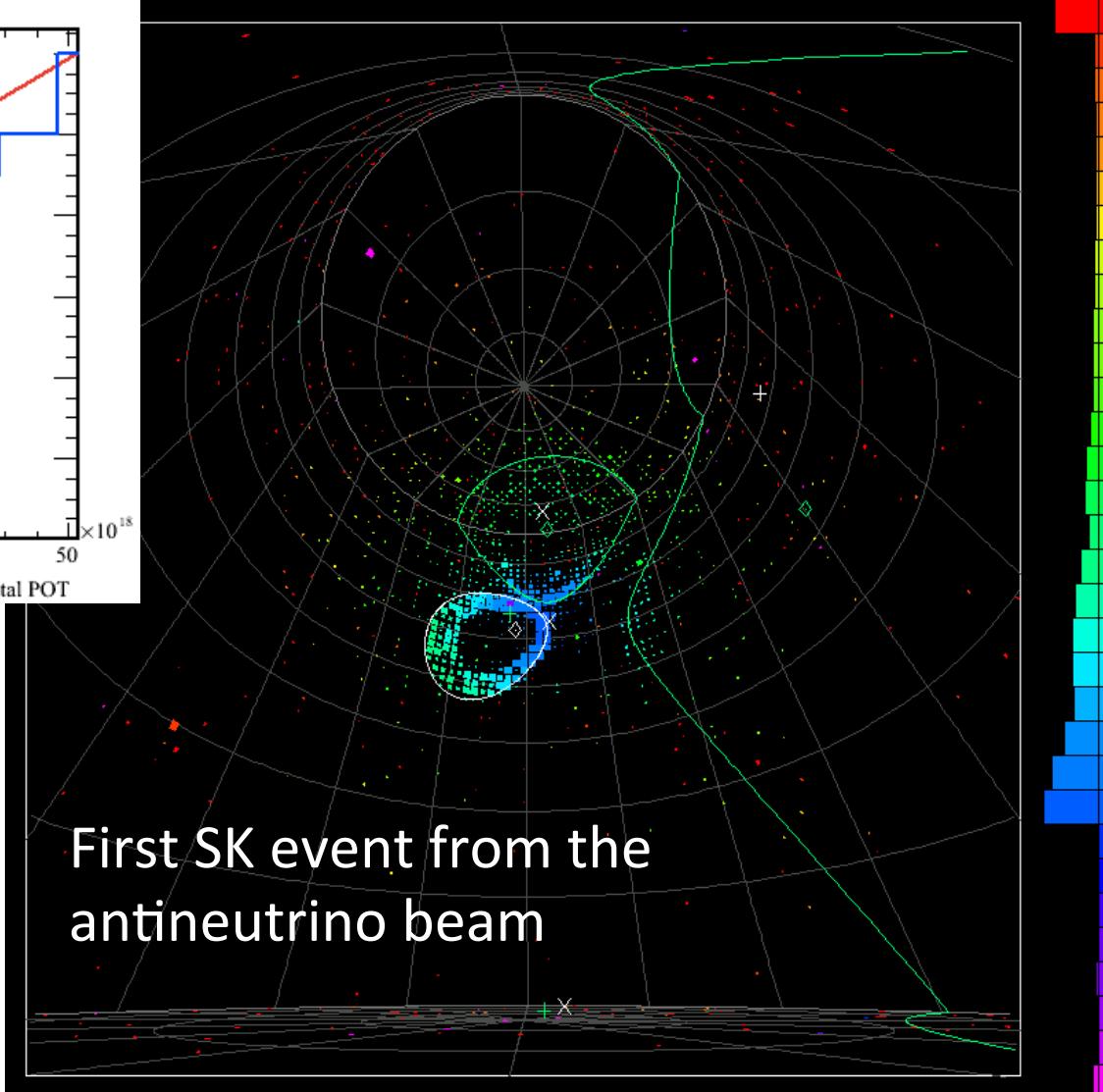
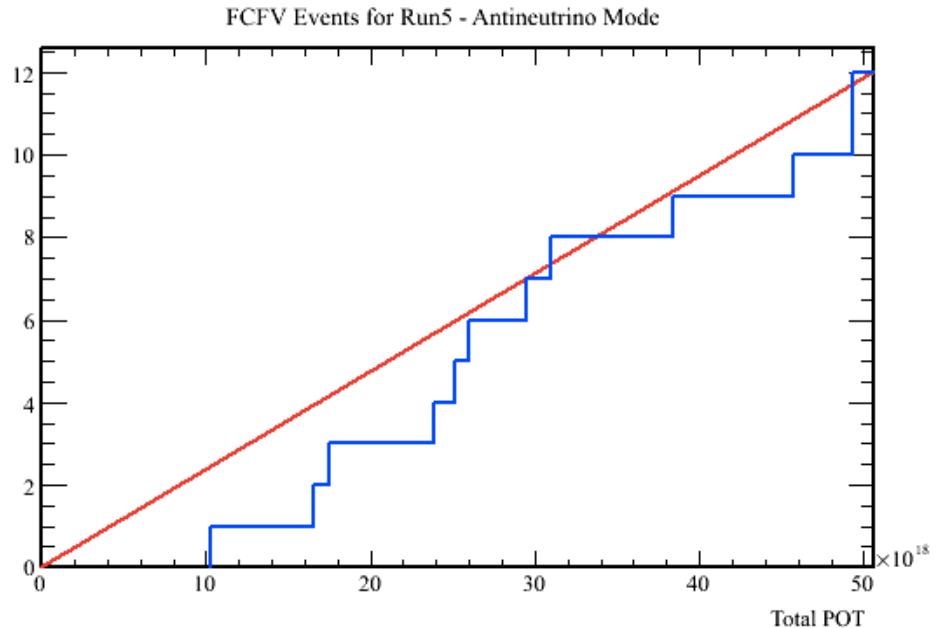


Alex Himmel

Submitted to PRD, arXiv:1410.8811 [hep-ex]
Comparison from PRD 86 (2012) 113014

$\sin^2 2\theta_{ee}^{69}$

Antineutrino Data



- We are now accumulating antineutrino data
 - 0.5×10^{20} POT
 - 12 FCFV events so far
- Look forward to analyses with antineutrinos soon

Conclusions

- We have used a narrow-band off-axis beam to measure three-flavor neutrino mixing
 - Most precise measurement of θ_{23} , favoring maximal disappearance
 - $>7\sigma$ evidence of ν_e appearance
 - First exclusion of a range of δ_{CP} : 27° – 149° at the 90% C.L. in NH
- We have used the ND280 detector to search for short-baseline oscillations to a sterile neutrino
 - Exclude a region of the gallium anomaly at the 95% C.L.
- We have taken our first antineutrino data
 - With 50% neutrino and 50% antineutrino data at our final exposure we may be able to see a hint of CP violation at the 90% C.L.
- As plans for the future of long-baseline neutrino physics are being made here at Fermilab, we are taking the first steps